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A Review of Oyster Culture and the Oyster Industry in North America[1]

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INTRODUCTION

Among the various marine species presently considered appropriate for intensive and controlled culture, the oyster is perhaps most prominent. Ryther and Bardach (1968) have described certain biological criteria that should be satisfied in order for a species to be adaptable to culture: responsiveness to efforts to effect reproduction under captive conditions; tolerance of eggs and larvae to the culture environment; nutritional requirements that may be easily satisfied in this environment; and a relatively rapid rate of growth from egg to maturity. To a large extent the oyster satisfies these criteria, and it possesses other favorable qualities as well.

The oyster is sedentary rather than fugitive; its lack of mobility subsequent to the planktonic larval period obviously eliminates certain problems in management associated with fugitive species. Since it is herbivorous, the oyster's nutritional requirements are more readily satisfied, and at greater efficiency, than are those of a carnivore. The oyster is highly fecund, a single female being capable of producing many millions of eggs at a single spawning. Finally, and of considerable importance with respect to economic considerations of aquaculture, oyster culture protentially is highly profitable and is a traditional industry in the majority of coastal states. Therefore, certain marketing and institutional constraints that might apply to the commercial culture of other species are, in the case of the oyster, avoided. The oyster's popularity for cultural purposes is further enhanced by the fact that oyster production during this century has undergone a severe decline, to the extent that the survival of the industry has been seriously questioned (Wallace, 1960). As a result of regional scarcity, e.g., the New England States, the oyster has become a luxury, rather than staple, food item in some areas, with a corresponding high market value.

The purpose of this report is to review the current status of oyster culture and the oyster industry in various geographical areas of North America. Although the initial purpose of this study was to describe recent techniques employed in culture, it quickly became apparent that the various approaches to, and methods of, culture reflected the socio-economic conditions of the industry in the area concerned. For this reason, this report will attempt to describe the various reasons as to why certain methods of culture have, or have not, been adopted, which, in addition to advances in technology, would include a broad spectrum of non-technical factors and constraints.

The subject of aquaculture is becoming of increasing interest, in this country and elsewhere. Despite its current glamour, however, the development of this industry will be impeded, and in certain areas prevented, by factors not necessarily technical in nature. Such factors will be discussed in this report. It is hoped that certain of the information contained here may therefore be of interest to those not necessarily engaged in oyster culture or in the oyster industry but rather in any form of coastal water use, since certain of the problems described are not restricted to the former group alone.

The information contained in this report was obtained by means of personal interview with members of the industry and with scientists involved in oyster research, and by a review of pertinent literature. In view of the large number of oyster culture and research operations and investigations being undertaken in North America, only representative groups and agencies could be contacted during the period allocated for this study. The interest and cooperation of those who provided this information are acknowledged in an appendix to this report.

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THE INDUSTRY

The oyster industry of North America is based upon four distinct species. Ranked in order of current importance, these are the American, or Eastern, oyster **(Crassostrea virginica)**; the Pacific, or Japanese, oyster **(Crassostrea gigas)**; the Olympia, or Pacific Coast native, oyster **(Ostrea lurida)**; and the European flat oyster **(Ostrea edulis)**. Systematic efforts to culture **O. edulis** in North America on a commercial scale are so recent that the economic significance of its production at present is negligible. With respect to **O. lurida,** production of this species has declined to the point where it represents only a fraction of one percent of total volume. The North American oyster industry, therefore, relies largely upon the production of the first two species, **Crassostrea virginica** and **C. gigas,** and, of the total annual volume currently produced, **C. virginica** accounts for nearly ninety percent.

According to Churchill (1920), the oyster industry was once the most valuable fishery in the United States. Within the past fifty years, however, oyster production for the country as a whole has declined by roughly fifty percent (Engle, 1966). The Atlantic Coast, from the Maritime Provinces of Canada to North Carolina, has witnessed the most spectacular decline. Since 1910, the major oyster producing states of Connecticut, Maryland and Virgina have declined by 97, 80 and 60 percent respectively. The reasons for this decline are numerous and varied and will be discussed on a regional basis further in this report. In any event, current production now approximates fifty million pounds annually, with a dockside value of roughly thirty million dollars, in contrast to a figure of over one hundred million pounds produced during the early 1920's.

Conversely, oyster imports have markedly increased, particularly during the past two decades. It is now estimated that over seventy percent of the canned oysters consumed in this country are imported (Wallace, 1969), primarily from Japan. This would reflect the fact that national demand for oysters remains high, and that it is becoming increasingly difficult for domestic oyster growers — particularly those on the West Coast — to compete with foreign production. According to Windham (1968), national oyster production, in pounds produced per capita, has declined from 1.02 in 1920 to 0.28 in 1965. Windham concludes that ". . . not only has oyster production failed to keep up with population growth in this century but it has actually been declining during a period of rapid population increase". There is some indication that the decline in oyster production has been accompanied by a shift in consumer preference to shrimp, the national consumption of which has almost tripled since 1950.

On the basis of these facts, the outlook for the oyster industry would not be considered encouraging. Its continuance would seem to be based at least partially on the fact that, in many areas along the coasts, it is a traditionalized industry and occupation. Presumably the majority of oystermen in certain areas are reluctant, or unequipped, to shift to other less arduous, more profitable, occupations. However, as is true of certain of the other fishing industries, the low socio-economic position of the oyster industry in relation to others discourages participation by younger and more innovative personnel.

If the industry is to progress from its present low level, a new technology, or aquaculture, must be developed. This will involve technological improvements over current methods of planting, rearing, harvesting and processing, and will involve greater use of artificial, as opposed to natural, environments for rearing oysters through various stages of their life cycle. As described in a recent report prepared by the American Cyanamid Corporation (1969), the shift in technique may be somewhat analogous to that experienced by the poultry industry in relatively recent years, by which the chickens are now produced from egg to market size rapidly, efficiently, and with hand labor reduced to a minimum. Whether the state-of-art of oyster culture will ever progress to this degree is speculative, but quite clearly the decline of the industry is in large measure attributable to inadequate understanding and gross mismanagement of the natural environment. Advances in the technology of oyster culture that may lead to systematic farming under controlled environmental conditions is one of the subjects of this report.

With respect to aquaculture, probably both the most primitive and the most sophisticated methods and approaches may be now found in the oyster industry; regional contrasts in technique make the science of oyster culture of particular interest. In those areas where new techniques have been developed and practiced, the industry may be on the verge of a major expansion. Conversely, there would appear to be little hope for further development of the industry in areas bound by tradition and antiquated legislation.

The Maritime Provinces

THE INDUSTRY

The oyster industry of the Maritime Provinces of Canada is based upon the production of the Eastern oyster (**C. virginica**) exclusively for the half-shell trade. In 1966, a total of 44,000 bushels of oysters were harvested in the Provinces of New Brunswick, Nova Scotia and Prince Edward Island. (Assuming a bushel to yield approximately 7 pounds of shucked meats, this level of production is nearly the same as that produced in the five coastal New England States — Maine, New Hampshire, Rhode Island, Massachusetts, and Connecticut — during the same period.) The dockside value was $560,500 (Morse, 1968). Prince Edward Island is the chief producer, accounting for up to ninety percent of total production in recent years.

Since 1928, oyster production in the Maritimes — with the exception of some peak years during the late 1940's and early 1950's — has been fairly stable. Since 1950, however, the price has risen steadily, from $2.60 per bushel in that year to over $13.00 per bushel in 1966. At the present time, a bushel of prime quality oysters, known as "fancies", may wholesale for as much as $35.00. In the ten-year period 1956-1966, total production has scarcely varied, but the total value has increased by 60 percent. (As will be seen, this general increase in the value of oysters relates particularly to the half-shell oyster, which is usually sold in expensive restaurants and hotels.)

The great majority of oysters produced in the Maritimes are sold in Quebec, primarily Montreal, with a small percentage — 5 to 15 percent — sold in Toronto (Morse, 1968). Very few are distributed west of Toronto or exported to the United States. Apparently a far greater volume of oysters could be marketed if available, particularly if increased production was accompanied by a modest decrease in price.

Historically, oyster production in the Maritimes reached a peak in the latter part of the 19th century. The combined factors of overfishing, disease, predation by starfish and elimination of beds by heavy stands of eelgrass resulted in a steady decline in production from the year 1890 to 1920. Production remained relatively stable during the period 1920 to 1940, increased to a peak in 1948, and then declined again to its current level. The increase during the 1940's is attributed in great part to the active encouragement of oyster growers by the Government to obtain private leases. However, an epidemic disease occurring in the early 1950's reduced oyster stocks to their present level (Medcof, 1961).

At the present time, the fishery is a primitive one. The majority of oysters are harvested by means of tongs or rakes. At the present, there are only three mechanical harvesters in the Maritimes. The individual leases are small, and a minimum capital investment is involved. For most of the oystermen, oystering is a part-time occupation supplemented by other forms of fishing and/or by unemployment compensation. There appears to be little incentive on the part of most of the fishermen to improve the quality of their product, even to the extent of removing mud from the shells prior to shipment, or to expand their level of operations. In fact, efforts by an individual or group to acquire large areas for lease would in all likelihood be resisted by the fishermen.

Morse (1968) has calculated that, under highly favorable circumstances, the Maritimes could produce in the neighborhood of 2.5 million bushels per year, an increase over current production by a factor of fifty-seven. In his opinion, the problem for the foreseeable future is not one of demand but of supply. The industry will either continue indefinitely at its present low level or, as a result of much greater capital investment, expand considerably. Morse feels that the determining factor will in all likelihood be the possible development of hatchery techniques for producing large quantities of seed oysters. Since the development of the industry must depend upon an increased supply of stocks, current efforts to increase the resource through culture methods will be discussed.

OYSTER CULTURE

According to Drinnan and Parkinson (1967), "A supply of seed oysters is the most pressing need of the oyster industry of the Maritime Provinces. Natural oyster production is extremely variable and steadily decreasing in the face of deleterious changes in our bays and estuaries brought about by man's activities. Attempts to utilize natural seed oyster production as efficiently as possible are continuing, but even at best the supply from this source is too small and too unreliable to support a healthy industry". (It might be noted that these authors could be speaking for the industry in the New England, Middle Atlantic, and Pacific States as well.)

The ability of the oyster to reproduce is related to water temperature. Although water temperatures in parts of Nova Scotia, New Brunswick and in the vicinity of Prince Edward Island do become sufficiently high during summer to stimulate spawning, the conditions for reproduction are rather marginal and inconsistent from year to year. The situation has become more acute as a result of dwindling parent stocks, which have been fished intensively and ravaged by disease. Thus, unlike the situation along the southern coast of the United States, where annual reproduction may be so intensive as to create a hardship in the industry through overcrowding and consequent stunting of young oysters, reproduction is the critical and chief limiting factor in the Maritimes.

In 1963, an Experimental Oyster Hatchery was constructed by the Fisheries Research Board of Canada at Ellerslie, Prince Edward Island. The function of this hatchery was to develop reliable techniques for oyster seed production under controlled conditions and, in the process, act as catalyst to development of private commercial hatcheries in the Maritimes. (Within the past year, and as a result, the first commercial shellfish hatchery in Canada was established on Prince Edward Island.)

Landers (1968), Ryther and Bardach (1968), and Webber (1968) have described in some detail the operation of a representative oyster hatchery in New England. In general, the operation consists of the following procedures:

1. Adult oysters are conditioned for spawning by manipulating the water temperature in the holding tank in such a way as to accelerate the process to gametogenesis. (Conversely, ripened adults may be prevented from spawning, if this is desired, by maintaining temperatures below 18°C.) Depending upon the nature of the water supply and the particular hatchery regime, the adults may or may not be fed cultured food during the conditioning process.
2. The oysters are induced to spawn by temperature manipulation, usually involving a sharp temperature increase to 30°C. (If thermal stimulation by itself does not stimulate spawning, suspensions of oyster gametes added to the spawning trays may trigger the spawning reaction.)
3. The eggs, once fertilized, are passed through fine sieves, to remove unwanted debris, and held in seawater at temperatures of 25 to 30°C. Depending upon the hatchery, this water is usually pre-filtered, and may be treated with antibiotics and exposed to ultra-violet light prior to use. In short, every effort is made to eliminate potential predators, competitors, and pathogenic organisms.
4. Within 24 - 48 hours, the eggs have developed into motile larvae; these are generally transferred to larger tanks (100 gallons or more in capacity) and held at specific densities. Again depending upon the particular hatchery, larval densities may vary from 15 larvae per ml of culture water to one larva per two to three ml, water temperatures may vary from 25 to 30°C, and the water may be changed daily, every other day, or less frequently. The duration of the larval period may vary from 10 to 20 days, depending upon temperature, population density, and abundance and quality of food.
5. Larval food, in the form of unicellular algae, is usually provided daily. The type of algal food culture, the method by which it is cultured, and the amount fed to the larvae varies from hatchery to hatchery. The favored larval food in certain hatcheries are the small naked flagellates **Monochrysis lutheri** and **Isochrysis galbana,** maintained in limited-volume unialgal cultures under generally aseptic conditions. Alternatively, cultures of mixed and unidentified species may be maintained by clarifying raw seawater by means of centrifuge, thereby removing algal predators and

competitors, and obtaining planktonic "blooms" by exposure to sunlight and by addition of inorganic nutrients. Finally, certain hatchery operations have been successful without providing supplementary food; raw seawater is simply passed through a filter of suitable porosity to remove predators and introduced directly into the larval tanks.

6. When the larvae attain "setting" size, i.e., when metamorphosis from the motile larval form into the sedentary adult form is initiated, they are transferred to setting tanks, which typically are provided with a layer of oyster shell upon which the young oysters attach during metamorphosis. (Recently, methods have been developed whereby the metamorphosing oysters are not allowed to become permanently attachd to a substratum, but rather are cultured as single, non-attached oysters.)
7. After a period of twenty-four hours, when the majority of the larvae have attached to the shell, the shell is transferred to plastic-mesh bags, and the bags in turn are suspended in holding tanks where the post-larval oysters are fed and grown as rapidly as possible. After the oysters have attained a size of three mm or so, the bags are transferred to the natural environment, where the young oysters become adjusted to more rigorous conditions during their early growth.
8. The final step in the hatchery process occurs when the juvenile oysters, having attained a size of approximately 12 mm (one-half inch), are planted on the bottom, where, it is hoped, they may mature to marketable size.

Under this generalized procedure, there are many variations in technique from one hatchery to another, which may reflect specific economic considerations, personal preference or bias based upon experience, ultimate objective, and even subtle differences in water quality. Many techniques employed in oyster hatchery facilities have evolved on a trial-and-error basis, and, in the opinion of many, the process of rearing oysters under hatchery conditions is considerably more of an art than a science. In any event, the broad objectives are the same, and, in areas such as the Maritime Provinces of Canada, the future of the industry may depend upon commercial hatchery programs.

Cultural operations at the oyster hatchery at Ellerslie, Prince Edward Island, differ from the generalized operation described above in certain important respects. First, although aseptic, unialgal cultures of **Monochrysis lutheri, Isochrysis galbana** and **Dicrateria inornata** are maintained as supplementary food, the major source of larval and post-larval food derives from large-volume, non-sterile continuous cultures maintained in 1000-gallon tanks. These tanks, located in a greenhouse and without benefit of artificial illumination, are approximately two feet deep. Food organisms may reach a density of one and one-half million cells per ml of culture. (Under sterile conditions and at small, e.g., five gallon volumes, **Dicrateria** cultures may reach 25 million cells per ml.) Anywhere from 10 to 50 percent of the culture is harvested daily, and the tank is refilled with filtered seawater. The water is enriched periodically with phosphoric acid and urea. No temperature control system is employed, but the water in the tank is constantly circulated by means of an auxiliary circulating pump that draws the water from the bottom of the tank and delivers it through a manifold at the surface. In this way, the cells are prevented from settling out and are provided continual exposure to the natural illumination in the greenhouse. The advantage of this food culture system is that the technical complexities of maintaining sterile cultures are avoided, and certain operating costs, e.g., artificial illumination, are eliminated.

Investigators at Ellerslie have also abandoned the use of 100-gallon larval tanks in favor of much larger, 350-gallon tanks. They have found that contamination in the larger container is much reduced, presumably due to the large volume-surface area ratio, and that antibiotics are no longer needed. The water in the larval tanks is changed daily; the larvae are inspected daily and measured every other day for growth.

The larvae are initially introduced into the larval tanks at a density of five million larvae per 100 gallons, or approximately 12.5 larvae per ml. At the time of setting, this number has been reduced by approximately 25 percent as a result of mortality and loss during water change. When held at 20°C, it requires 19 - 21 days for the larvae to reach setting size at this facility.

As indicated earlier, the purpose of the hatchery facility at Ellerslie has been to test and develop various techniques that might be useful in a commercial hatchery, and to assist members of the industry in developing their own hatchery facilities. One commercial hatchery is now in operation near Ellerslie. The building, 60′ long and 28′ wide, is a single-story, concrete floor structure that cost 25 thousand dollars to construct, excluding labor costs. For this facility to operate at a profit, it must produce at least two million seed oysters each year, a seed oyster being anywhere from one and one-half to two and one-half inches in size. Compared with the larger hatchery facilities in Connecticut and New York, this is a very small operation, with only three employees involved. It reflects the fact that production of a relatively small number of quality oysters in the Maritimes may bring a good profit to the producer.

In this hatchery, the spat are collected either on sea scallop shells, or on wood-veneer rings coated with a sand-cement mixture. If a sufficient amount of algal food is available — which, in the case of unialgal cultures, is maintained in sterile glass carboys, and, in the case of mixed cultures, in outdoor tanks — the spat are held in the hatchery for a period of two weeks. Otherwise, they may be put out in nature immediately after setting. The shells or wood-veneer rings are either suspended from rafts or held in floating trays until the oysters have reached a size of one half inch or more, at which time they are relatively safe from starfish and siltation and may be planted on the bottom. Under this system, it has been found that an oyster spawned in the hatchery in February may have reached two inches in size by the end of summer. At this size, natural mortality approximates only five percent per year. (In the Maritimes, it generally requires an oyster four to five years to attain marketable size when cultured on the bottom; they may reach the same size in two years when cultured in suspension off the bottom.)

The oyster industry of the Maritimes, despite its primitive condition, would seem to have great potential. The construction of roads and farming operations has resulted in erosion and consequent siltation of once-productive oyster beds (R. E. Drinnan, Personal Communication), but Morse (1968) has estimated there being at least 5,000 acres of bottom suitable for culture, and possibly twice this amount. Morse has further calculated that 10,000 acres could produce two and one-half million bushels per year. At current average wholesale prices of $20.00

per bushel, the potential value of the Maritime oyster fishery would be 50 million dollars, or nearly twice that of the entire United States. Although such intensive use of the oyster beds seems unlikely at present, there is an obvious opportunity for expansion of the industry.

The New England States

THE INDUSTRY

The New England States have experienced the sharpest decline in oyster production of any region in North America. Over 26 million pounds of oysters **(C. virginica)** were produced by the four States of Maine, Massachusetts, Rhode Island, and Connecticut in 1910, or nearly the same amount as is produced by the entire country today. Since that date, production has dwindled, almost steadily, to a current volume of less than 400 thousand pounds, or less than two percent of production in 1910.

The history of the oyster industry in New England is somewhat similar to that of the Maritime Provinces. As production has declined, the oyster has become increasingly a luxury item, particularly within the last two decades. (In 1965, New England oysters were worth roughly three times their 1953 value.) New England no longer supports an appreciable oyster shucking industry but relies almost exclusively on production of half-shell oysters for hotels and restaurants. In recent years, oysters grown in the waters of Cape Cod, Massachusetts, have commanded a price of $22.00 per bushel, wholesale; in Long Island Sound, the price has fluctuated closely around $18.00 per bushel. Were it not for the high public demand for New England half-shell oysters it is doubtful whether there would be any oyster industry remaining in this area today.

At one time, much of the New England industry was based upon the production of seed oysters along the Connecticut shore, which were transplanted to private beds in Rhode Island, Massachusetts and other areas. Since the turn of the century, this source of supply has diminished as a result of consistent set failure. Loosanoff (1966) states that, during the period of 1925 to 1961, good commercial sets occurred in only eight of the thirty-seven years. In an area where growth rate is relatively slow, i.e., a minimum of from four to five years to attain marketable size, and where natural mortality from predators, siltation and hurricanes has been extremely high, such reproduction has been insufficient to sustain the population.

The reasons given for failure in natural reproduction are varied. According to Sweet (1941), they would include a) misuse of shoreline areas, e.g., dredging and filling of marshlands and estuaries, and neglect of the inshore adult oyster beds, b) natural predation, c) adverse weather condition, e.g., prolonged cold spells during the spawning season, hurricanes, etc., and d) pollution of the coastal waters by industrial and domestic wastes. Certainly the steady deterioration of the shoreline environment must be a significant factor. The waters of Long Island Sound, the major producing area, which seldom exceed 20° to 21°C during the summer, are regarded as too cold for successful reproduction. Although oysters will spawn at this temperature, the larval period would be so prolonged as to minimize chances of survival. It is believed, therefore, that the majority of the larvae derive from the warmer rivers and estuaries, and it is the parent populations in these areas that have largely been eliminated as a result of shoreline development.

Although set failure has been one of the major reasons for the industry's decline, other factors have been involved as well. In Long Island Sound, two predators — the starfish **(Asterias forbesi)** and oyster drill **(Urosalpinx cinerea)** — have caused extremely heavy mortalities, particularly among the young oysters that were fortunate enough to set. In certain of the brackish water areas considered potentially favorable for reproduction, partially because the two predators cited above are excluded, intensive sets may be eliminated in a matter of days by the predatory flatworm, **Stylochus ellipticus.** Extensive winter-kills occur when severe cold spells coincide with unusually low tides. During the past three decades, major hurricanes in the New England area have destroyed beds in the Narragansett Bay (Rhode Island) and Long Island Sound areas, which were traditionally the leading oyster-producing areas of the North Atlantic.

The oyster fishery in New England traditionally has been a private fishery and remains so today. However, in contrast to the oyster fisherman of the Maritime Provinces, whose total equipment may consist of a skiff and a pair of tongs, the oysterman of Long Island Sound has a considerable investment in vessels and power dredging equipment, and, more recently, in an oyster hatchery facility. Certain of the oyster companies have several thousand acres under lease. Skindivers may be employed on a full- or part-time basis to make direct observations on the oyster beds, primarily to determine whether invasion by predators is occurring. Sophisticated techniques for eliminating predators through application of specific chemicals have been adopted. Without question, oyster farming has reached its most advanced state in the New England area, where the current methods employed are quite analagous to contemporary terrestrial farming: rearing of the young, during the most sensitive stages, under controlled environmental conditions; preparation of the planting grounds by removal of predators; and continual supervision and protection of the young oysters once they have been planted in nature.

Despite these technological advances, it is highly doubtful whether the New England States will ever produce oysters in the volume that they once did. Of the 60,000 acres under the jurisdiction of the Connecticut State Shellfish Commission, approximately half are closed to oyster production because of domestic pollution. In the opinion of some, the ecology of Narragansett Bay has been so altered by industrial pollution that it is no longer capable of supporting oysters in any quantity. Whether water pollution detrimental to the industry is alleviated in the near future is regarded as highly doubtful by prominent members of the industry.

The New England area is faced with other difficulties regarding possible expansion of the oyster industry. In States such as Rhode Island and Massachusetts, it is exceedingly difficult to obtain exclusive fishing rights to areas of coastal water. Legislation regarding private lease is restrictive, and there are increasing conflicts between commercial and recreational interests. It is partially for these reasons that the American Cyanamid Company undertook a recent feasibility study involving the culture of oysters, from fertilized egg to marketable size, under completely artificial conditions, with the awareness that use of natural areas for oyster culture was becoming increasingly limited. Shaw (1962) and Matthiessen and Toner (1966) described certain of the advantages of culturing oysters by suspension methods in New England; aside from the potential damage to rafts or other floating devices from storms or ice, however, the chief limitation upon raft culture is the difficulty in obtaining culture rights in suitable areas.

To summarize, the New England oyster industry has managed to survive, in the face of increasing scarcity of oyster stocks, because 1) scarcity has been accompanied by a marked increase in the market price of New England oysters, and 2) the industry has been assisted, and has assisted itself, by technological developments in culture. Certain of these developments will be discussed below.

OYSTER CULTURE

The center of shellfish research in the New England area is the U.S. Bureau of Commercial Fisheries Laboratory at Milford, Connecticut. With respect to oyster culture, perhaps the most significant contributions of this research facility have dealt with a) methods of supplementing natural oyster populations through artificial reproduction, i.e., hatcheries, and b) methods of preventing loss of the oyster crop through natural predation. More recently, genetic studies have been initiated at this facility, with interest focussed on such subjects as the effects of inbreeding on subsequent generations, selective breeding for favorable growth rates, hybridization, and genetic effects resulting from irradiation experiments. Although these studies are long-range, they reflect the emergence of oyster culture in the New England area as a science analogous to terrestrial agriculture.

Methods of supplementing natural reproduction by means of hatchery techniques were first explored in the New England area by W. H. Wells in the 1920's, when it was already recognized that set failure was perhaps the industry's greatest problem. Wells' experiments in inducing oysters to spawn under controlled conditions and in rearing the larvae through metamorphosis were further extended by personnel at the Milford facility (Loosanoff and Davis, 1963). The basic procedures in hatchery culture were sufficiently established for private oyster growers, in the early 1960's, to develop their own artificial rearing facilities. At the present time, five private oyster companies in the Long Island Sound area are equipped to produce oyster seed under artificial conditions.

The basic procedures in the typical oyster hatchery have already been described. Some hatcheries, however, rely exclusively upon the centrifuge method for raising food for the larvae, whereby seawater is passed through a continuous centrifuge, and all of the zooplankton and the heavier species of phytoplankton are removed. The smaller phytoplanktonic species remaining in the effluent are encouraged to bloom, by exposure to light and heat, in large tanks. The advantages to this method are that large volumes of algae may, when conditions are suitable, be cultured without dependence upon complex and aseptic culture techniques. The disadvantages are that an adequate supply of food cannot always be guaranteed, since the system depends upon a) there being an adequate number of appropriate phytoplanktonic species in the seawater supply, and b) there being a sufficient amount of natural radiation to insure photosynthesis in the large culture tanks. At certain times of year, or during periods of extended fog, the amount of food provided by this method may not be sufficient to satisfy the requirements of a large hatchery.

Other hatcheries may rely for their food supply upon maintenance of unialgal cultures, generally cultured in batches rather than on a continuous basis. In this procedure, isolated cultures of a particular species, i.e., Monochrysis, Isochrysis, etc., are generally obtained from either the Milford laboratory or the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts, where stock cultures of various species are maintained routinely. Using this as an inoculum, cultures are transferred to successively larger containers, e.g., from 100-ml flasks to 2,000 ml flasks to five-gallon carboys, and eventually to tanks several hundred gallons or more in capacity. Since far higher population densities may be obtained with unialgal cultures than with mixed cultures, this system requires less space and tank volume than the centrifuge method in order to produce an equivalent amount of food. However, in order for high concentrations of the selected species to become established, considerable precautions must be taken against contamination, the cultures must be aerated and illuminated constantly, inorganic nutrients and vitamins must be provided, and, for most species currently considered of nutritional value for oysters, the temperature must be maintained in the vicinity of 20°C. Therefore, maintaining a series of unialgal cultures requires constant attention, a certain expertise, and equipment that may be expensive, e.g., sterilizing devices, constant-temperature rooms, air compressors, fluorescent lighting, etc.

Certain hatcheries have adopted both methods as supplementary to one another, or to be used alternatively in the event one fails. Unialgal cultures of suitable species may be used as an inoculum to centrifuged water to accelerate blooms in large tanks.

Since the production of food is one of the most critical functions in a hatchery, the procedure adopted by one hatchery facility in Connecticut may be worth describing in more detail. In this case, four species of algae are maintained in culture: two diatoms **(Cyclotella nana** and **Phaeodactylum tricornutum),** one green alga (reportedly **Chlorella sp.),** and one naked flagellate **(Monochrysis lutheri).** The daily food requirements of this hatchery are 2000 gallons per day, at a cell concentration of 4–6 million cells per ml of culture.

The cultures are initiated in small flasks, which, as the cultures develop, are used to inoculate five-gallon carboys. Three carboys, in turn, are used to inoculate tanks of 1000-gallon capacity. These are rectangular tanks, approximately two feet deep, located in a greenhouse abutting the main hatchery building. They are aerated constantly and provided with an injection of pure carbon dioxide once each day. Each tank is illuminated by four flourescent bulbs and by natural light entering the sides of the building. During cold weather, the water in the tanks is heated by means of electric immersion heaters. Since these cultures cannot be protected from contamination in the open greenhouse tanks, they are generally harvested three days after inoculation.

The operator of this hatchery estimates that it costs approximately two cents to produce a gallon of food in this manner. One cent covers the cost of labor, while the other covers operating expenses, e.g., heat, light, etc. Since this particular hatchery may require 600,000 gallons of food during a year, $12,000 may be expended annually for food costs alone.

A totally different method of food culture has been tested at the Milford laboratory, whereby cultures have been maintained on a continuous, rather than batch, basis. In this case, artificial seawater, i.e., Rila Salts, is used as the culture medium; contaminating organisms that might occur in the seawater or in the seawater systems are thereby avoided. (In a large commercial operation, obviously the cost of the salts would have to be considered.) The species tested to date has been **Monochrysis lutheri.** The culture tanks, four feet by five feet by one foot deep, are illuminated constantly by eight Cool White fluorescent lamps and aerated continuously by two air stones. The room temperature is maintained at 20°C. Cell concentrations under these conditions have reached five to six million cells per ml, and the cultures have been maintained for several months at a time. Fractions of the culture are harvested daily and replaced with equivalent volumes of artificial seawater.

Part of the research program at Milford involves an evaluation of the various hatchery techniques that have developed in recent years, in order to analyze their respective advantages. This would include a comparison between centrifuged and filtered seawater as a culture medium for food organisms; the effectiveness of different types of antibiotics; the influence of population density and food concentration upon the growth and survival of larvae; etc. As far as the New England industry is concerned, the hatchery concept is of extreme importance to its well-being, not only as a means of supplementing natural recruitment, but as a means of selective breeding for desirable qualities, i.e., rapid growth rate, desirable shape for the half-shell trade, resistance to disease, etc. By continually discarding slow-growing larvae, one hatchery reportedly produces oysters that achieve marketable size significantly faster than their wild relatives.

It is difficult to obtain a clear picture of the economics of a hatchery operation at the present time. They have been in practice for such a relatively short period of time that a realistic picture of their "return on investment" cannot be given with certainty. The general opinion is that no hatchery at present is paying its own way, i.e., the value of the hatchery-reared oysters that ultimately have been harvested for market has not covered the cost of the hatchery's operating expenses, but this situation appears to be improving. To date, the major problem has been the high percentage of hatchery-reared oysters that have failed to survive once they have been planted in nature.

A modern large-scale hatchery represents a considerable investment. It is estimated that current replacement costs of one New England hatchery would approximate 300 thousand dollars. Its annual operating costs approximate 50 thousand dollars per year. Such a hatchery might produce 5,000 bushels of shell with hatchery-reared oyster spat attached — it is estimated that one such bushel contains three to four thousand spat — at an approximate production cost of $10.00 per bushel.

One oysterman has expressed the opinion that, for every bushel of hatchery seed planted, three bushels of mature oysters should be harvested. Should this be the case, at the current price of $18.00 per bushel, the return on 5,000 bushels of seed planted would be $270,000, and the margin between this sum and production costs, i.e., $50,000, would seem more than sufficient to defray expenses involved in transplanting from one bed to another, predator control, and eventual harvesting. On this basis, it would seem that the producer is not, as yet, realizing a three for one return on his hatchery oysters, but perhaps closer to one bushel in return for every bushel planted. Since an average bushel of marketable oysters contains roughly 250 oysters, mortality among hatchery-reared oysters on the beds may approximate ninety percent or more. Therefore, as Landers (1968) points out, ". . . no review of oyster hatchery potential would be meaningful without pointing out the absolute necessity for improved predator control and handling techniques for hatchery-reared seed after it has been transplanted to the field".

In the opinion of one biologist, if such techniques were adopted, hatchery production would, and should, be purely supplementary to natural recruitment. By placing greater emphasis upon management of natural beds, oystermen could expect a far greater return from natural reproduction, and at considerably less expense than through hatchery operations. Management policies would include a) proper preparation of setting beds, which would include elimination of predators, i.e., starfish and oyster drills, and removal of silt immediately before and after setting, b) careful monitoring of larvae to determine both when and where the cultch should be spread, c) the use of dock-dried shell, rather than recently dredged shell, as cultch, d) the systematic control of predators once setting has occurred, and e) transplantation of the young oysters in early spring as a means of preventing mortality by siltation. It is estimated that, as a result of these practices, the current volume of production from Long Island Sound could be increased 100-fold. Hatcheries would be held on a stand-by basis, to operate only in those years when natural reproduction failed.

In Long Island Sound, the two most effective methods of predator control are the spreading of quicklime on the oyster beds to destroy starfish, and the spreading of Polystream, a mixture of chlorinated benzenes that is toxic to oyster drills. When starfish are detected upon the beds, lime is spread at a rate of one ton per acre. Although liming in such quantity may become expensive — it has been estimated that one grower may spread $100,000 worth of lime each year — it is believed that every dollar invested in lime may save 25 dollars worth of oysters. Polystream is spread at similar concentrations, either in a sand mixture or in the form of granules. Since this material is only slightly soluble, it may, if not silted over, retain its effectiveness for two years or more. Polystream, because of its possible toxic effects upon other organisms, has not been cleared for general use in States other than New York or Connecticut, where extensive monitoring tests have been undertaken for several years.

If better management of the natural beds is one alternative to hatchery operations, another is the intensive use of natural areas, such as salt ponds, for seed production. Although most efforts in this direction have not been particularly successful (Matthiessen and Toner, 1966), at least one pond culture operation in the New England area has been able to produce seed oysters in quantity consistently since its inception in the early 1960's. The company, located at the eastern end of Long Island Sound, currently produces approximately 15 thousand bushels of seed oysters each year, which are sold to the Sound oystermen for planting on their grounds. One producer has reported a return of three bushels on every bushel planted.

The procedure for collecting seed oysters is as follows. During the winter, as many as 60,000 strings of bay scallop shell, consisting of pairs of scallop shell threaded on 14-gauge galvanized wire, are constructed. There are 74 shells to a string, each pair separated by a two-inch plastic tube spacer, and the strings are eight feet in length. In early summer, the strings are loaded on a series of wood-and-styrofoam rafts anchored in a 23-acre, brackish water pond. The pond usually communicates by means of a tidal creek with Long Island Sound, but prior to the spawning season, the pond is closed off to accelerate rise in water temperature and to prevent escapement of the larvae. When the parent oyster population in the pond spawns, an event that generally occurs when water temperatures reach 23°C and that is detected by larval sampling, the shell strings are suspended from the rafts. After setting has been completed, the pond is reopened. The oysters are harvested from the pond the following spring, when they are approximately nine months of age and average one inch in length.

It is not entirely clear why this pond, in comparison with others in the New England area that would appear suitable for oyster seed production but in fact have not proven to be so, has succeeded in obtaining oyster sets every year. It is conjectured that the relatively large depth: surface area ratio, combined with the fact that high hills surround much of the pond and shield it from prevailing winds, contribute to a stable temperature regime. Absence of freshwater inflow in the form of springs or creeks also contributes to a relatively stable salinity regime.

The direction of oyster culture in New England may be influenced by two relatively recent phenomena that have potentially beneficial implications. The first involves techniques for obtaining seed oysters free of cultch in a hatchery, a process first developed on a commercial scale in 1967 by Pacific Mariculture, Inc., in Pescadero, California. Information on the particular technique employed by this company is not available; however, other commercial hatcheries and research groups have developed methods of obtaining "cultchless" oysters since this time, which will be described at greater length below.

The advantage of obtaining cultchless oysters, whereby the oysters are grown singly and unattached almost immediately after metamorphosis, lies in the following: 1) one of the major expenses in a hatchery operation, i.e., providing a suitable cultch that is clean and non-toxic, is eliminated; 2) the oysters, growing as singles and separated from one another, produce a desirable shape, an important feature of the half-shell trade; 3) since the oysters are separated, competition for food may be less and growth rate improved; and 4) very large quantities of oysters, by number, may be handled and shipped for planting in other areas.

Despite these advantages, there are serious disadvantages as well. Single oysters three to four mm in size cannot be planted directly on the bottom without unavoidable loss through siltation, transport by currents, etc. Furthermore, small unattached oysters appear to be readily devoured by bottom-crawling predators that otherwise would not be considered a serious problem. Therefore, these oysters must be raised in trays or other floating devices until large enough, i.e., at least one inch in size, to plant on the bottom. In areas where fouling is heavy, this system will require continual maintenance and cleansing of the trays, which will involve extra time and labor, and hence expense. For this reason, the benefits of cultchless oysters may be limited to areas where fouling is negligible.

The second phenomena concerns the use of effluent cooling water from electric generating plants as a source of culture water for oyster hatcheries and for rearing the post-hatchery stages. Since warming of seawater is one of the major expenses in a New England hatchery, operations have generally been restricted to the warmer months. One hatchery facility is presently being constructed adjacent to a plant effluent on Long Island Sound, where water temperatures are raised by 7° to 10°C as the water passes through the cooling system. Juvenile oysters have already been cultured successfully in the vicinity of the discharge, and it would appear that the use of this pre-heated water for hatchery purposes would greatly improve the economics of a hatchery operation (Webber, 1969).

In summary, the most progressive changes in oyster culture and in the oyster industry have occurred in New England, where, until very recently, the outlook was grimmest. A dwindling supply has led to increase in value of the product, which in turn has encouraged a substantial increase in investment in the industry, particularly in terms of technological improvement. Major problems still remain, including pollution and restrictive legislation regarding private leasing of natural areas, and it would seem doubtful whether a significant amount of new area can be brought into production. However, the combined efforts of hatchery seed production and predator control have prevented the industry from going under completely, and may lead to far more intensive production on existing leases free of pollution.

The Middle Atlantic States

THE INDUSTRY

The Middle Atlantic States include New York, New Jersey, Pennsylvania and Delaware. Since oyster production in New York derives almost entirely from Long Island Sound, which has been considered earlier under the New England States, and since oyster production disappeared in Pennsylvania during the first decade of this century, only New Jersey and Delaware will be considered here.

Oyster production in these two States is confined for the most part to the Delaware River, where, in its lower reaches, pollution has not been as intensive as in the shallow coastal bays. From 1880 to 1930, average annual production approximated two million bushels annually. After 1930, production declined to approximately half this volume, as seed oysters became scarcer. In 1957, the Delaware River population was almost eliminated by disease, the cause of which was attributed to multi-nucleated spheres designated as MSX and later identified as a protozoan. (The scientific name of the causative organism is **Minchinia nelsoni.)** Production declined to an all-time low of 10 to 15 thousand bushels annually, and only very recently has volume increased. In 1966, New Jersey and Delaware combined produced slightly over 700 thousand pounds of oysters, valued (wholesale) at slightly over 800 thousand dollars. The fishery is largely a private one, with the grounds under private lease, although the seed beds are State controlled.

As indicated earlier, oystermen in Massachusetts and Long Island Sound currently receive \$22.00 and \$18.00, respectively, per bushel of high-quality oysters, i.e., those destined for the half-shell market. The average price for Delaware River oysters is only \$6.00 to \$8.00 per bushel, although those culled for the half-shell market may receive \$12.00 to \$14.00 per bushel. These make up a very small percentage of the total, however, as the majority of the oysters harvested are shucked rather than sold in the shell.

As is true of the industry in New England, the major current problem in this area is an inadequate amount of seed oysters, since many of the seed beds were eliminated by the disease MSX. At the present time, oyster growers rely upon seed obtained reasonably far up the River, where salinities may drop to a low enough level to prevent infection. (The MSX organism apparently cannot tolerate salinities below 10%.) The seed oysters are brought down-River for final growth and fattening, but, as a result of mortality, one bushel of seed yields only one bushel of mature oysters as a rule. Each bushel of seed costs the grower approximately two dollars.

Since 1960, much of the oyster research in these two States has concentrated upon methods of producing seed oysters that are resistant to MSX, using hatchery techniques developed in the Northeast. Although the industry may in fact have very little alternative, the economic justification for such an approach would seem questionable in view of a) the high cost of hatchery operations, and b) the low market price of oysters in this region. However, since resistance to MSX appears to be hereditary, gradual stocking of parent beds with oysters of a resistant strain may have a long-range beneficial effect upon the industry.

OYSTER CULTURE

Two hatchery operations have been initiated in the Delaware River area, neither of which are commercial but rather experimental in purpose, under control of the State Universities of New Jersey and Delaware. To date, these facilities have not been concerned with large volume production of seed oysters but primarily with development of techniques that are both suitable and economic for the region concerned. However, with assistance in the form of Federal funding, a pilot shellfish hatchery is currently being developed in Delaware, at which efforts will be made to determine the technical and economic feasibility of rearing oysters from fertilized egg to marketable size under completely artificial conditions, as well as of rearing large numbers of disease-resistant seed oysters for planting in nature.

The major difficulty faced by hatchery workers in this area initially was the difficulty in inducing adult oysters to spawn in the laboratory. Oysters from New Jersey southward have been found to be unresponsive to techniques developed for, and used successfully with, New England oysters (Loosanoff and Nomejko, 1951). Although gametes can be obtained by stripping the ripened adults, this is not desirable, as Hidu et al. (1969) point out, ". . . if the hatchery is to maintain brood stocks of desirable genetic strains, since parents must be sacrificed". Whereas northern oysters are relatively quick to respond to thermal and chemical stimulation, it has been found difficult to induce oysters south of New England to spawn, particularly "out of season", i.e., summer, fall, and winter.

At the Delaware hatchery facility, a system recently has been initiated whereby oysters may be induced to spawn on a year-around basis. The parent oysters are taken from nature in spring, before water temperatures have exceeded 15°C. These are held in tanks in the laboratory through which Delaware Bay water flows constantly, and the temperature of which is maintained at 15°C. Several weeks prior to the date at which spawning is desired, the oysters are exposed to higher temperatures, i.e., 20° - 24°C, and water flow is increased to provide adequate food. (In this system, the only treatment of the water is that of temperature adjustment by means of heat exchanger.) A final elevation of temperature, e.g., to 30°C, may be sufficient to trigger spawning.

One of the interesting features of the Delaware rearing facility is the fact that the larvae, held at concentrations of 10 per ml of culture media, do not require supplementary food. Reportedly, raw seawater is passed through a bag filter of five micron porosity and held in greenhouse tanks for a period of 18 hours, after which this water is used to fill the larval tanks. Apparently sufficient food organisms are present to sustain the larvae if the water is changed every other day. If such a procedure can be applied during most months of the year, and at large volume, one of the major problems in hatchery programs, i.e,, supply of adequate amounts of suitable food, would be eliminated. Obviously, this technique is highly dependent upon location and the nature of the water supply. The hatchery facility in New Jersey, which had initial success with this general procedure, can sustain larvae in natural seawater, without supplementary food, for at least six months of the year (May - October.)

In summary, the major research effort in both these States in recent years, as a means of supplementing dwindling stocks, has been directed towards artificial culture techniques, with the hope that the natural beds decimated by MSX may gradually be replenished with disease-resistant strains. Private industry has yet to take an active part in this effort, in contrast to Long Island Sound where certain of the major technological achievements have been accomplished by private oystermen.

The Chesapeake Bay

THE INDUSTRY

Chesapeake Bay traditionally has been the leading producer of oysters in North America. In 1966, slightly over 21 million pounds of oysters were harvested from the waters of Maryland and Virginia, or roughly 40 percent of the total production in the United States. The value of the harvest was slightly over 14 million dollars, or approximately half the national total.

Despite these figures, current production is only one-quarter of what it was at the turn of the century, when almost 80 million pounds were harvested. During the period 1930 - 1960, production was relatively stable, averaging slightly over 30 million pounds annually as the value increased from 12 cents per pound to nearly 70 cents per pound, wholesale. However, production has dropped by one-third during the 1960's, and there is little indication of an upsurge in the industry in the near future. Although Maryland production was up substantially during 1967, reflecting an increase of 150 percent over 1964, production in Virginia declined both in 1967 and 1968.

The reasons for decline in oyster production in the Chesapeake are varied and complex. Certainly gradual environmental deterioration of seed-producing areas, through pollution and siltation, and heavy mortality resulting from invasion of MSX in the more saline areas of the Bay in recent years, are partially responsible. However, as Andrews (1968) has pointed out, the Chesapeake is, in comparison with other major oyster-producing areas, relatively free of predation, disease and loss through hurricanes. In the opinion of many, adverse environmental factors are incidental to more deep-rooted ailments in the industry, which are largely social, economic, and legal.

The Chesapeake oyster fishery is largely a public, State-subsidized industry. In Maryland, of the nearly 350 thousand acres that are designated as oyster-producing grounds, only 10 thousand are privately leased, and these are distinctly inferior grounds. In Virginia, public attitude and legislation regarding private leases are more enlightened; almost 40 percent of the total oyster-producing acreage (nearly 350 thousand acres) are privately leased. (It is of interest to note that, although private leasing is restricted to inferior grounds, production per acre in 1966 averaged nearly 25 bushels for private grounds, as opposed to less than five bushels for the public beds, in Virginia.) However, efforts to expand the number of private leases are bitterly, and effectively, opposed by the Bay watermen, who consider the fishing grounds, and the oysters thereon, as common property to be shared by State residents.

In comparison with the situation in Long Island Sound, the private leases that do exist are rather small, in addition to being poor in quality. In Maryland, the average size of a private lease is only 13 acres.

According to Staples (1967), Maryland expends nearly two million dollars annually in oyster propagation. Much of this effort involves the dredging and planting of shell as a means of sustaining the dwindling seed oyster supply and rehabilitating natural beds. Virginia pursues a similar program. The seed is subsequently transplanted on public beds or sold to private grant-holders. Private growers in Virginia may pay from $1.00 to $2.00 per bushel for seed, with an average count of 1000 seed per bushel. From this, he can expect at least a one for one return, and possibly as high as three bushels of marketable oysters for every bushel of seed planted. In Virginia, the current price of oysters falls within the range of $4.00 to $6.00 per bushel. (The maximum price for Maryland oysters, excluding those produced in Chincoteague Bay for the half-shell trade, is about $5.00 per bushel, although during 1969 prices dropped as low as $2.50 per bushel. The Chincoteague oyster, which has a salty flavor, is sold by the fishermen for the half-shell trade at prices approximating $12.00 per bushel.) In most instances, the private grower in the Chesapeake pays little attention to his beds between the time the seed is planted and the time the mature oysters are harvested, two or three years later.

Manning (1968) has pointed out that, despite the increase in oyster production in Maryland in recent years, i.e., since 1964 and resulting largely from a heavy set in the Potomac River, the price has remained stable, therefore indicating that over-production is not a problem. (In fact, in recent years, processors in the Chesapeake region have imported oysters from the Gulf States in order to sustain supply.) The great majority of oysters produced in the Chesapeake are shucked and sold as fresh-shucked raw meats, although a portion are breaded for frying. In general, one bushel yields approximately six pints. In recent years, large quantities of smaller sized oysters have been sold to the soup industry. Although the fisherman receives a lower price, i.e., $3.00 to $4.00 per bushel, for these oysters, this activity has helped stabilize the industry at a time when disease had eliminated much of the larger stock.

The oyster fishery is conducted in very primitive fashion. The majority of oysters are harvested by tongs; the use of dredges and, in Maryland, engines are either prohibited or else a permit is required. The oysters are rarely culled but delivered to the shucking houses in company with empty shells, juvenile oysters and debris (Bailey and Briggs, 1968). (In Maryland there is a cull law that prohibits taking oysters less than 3" long and allows only 5% shell and debris in any one bushel.) In 1967-68, a total of 4,229 tongers but only 42 dredges operated in Maryland (Manning, 1968).

Traditionally, the chief seed oyster producing area for Virginia in the Chesapeake Bay has been the James River. Since 1960, however, this area has received only two sets of commercial significance. In 1963, a moderate set occurred in the Potomac River, which, as a result, has produced a significant portion of the seed since 1965.

Whether or not, as a result of State efforts to augment the local supply of seed oysters, the Chesapeake oyster industry will recover from its generally downward trend remains to be seen. Certainly, it has failed to encourage the type of private effort that has been necessary to sustain the Long Island Sound industry, through restrictive legislation on private leasing and methods of harvesting, and current market prices would tend to discourage substantial investments in any event. Furthermore, although fresh shucked oysters comprise the backbone of the industry, efficient and mechanical methods of shucking have not yet been brought into general practice, and it has become increasingly difficult for shucking plants to attract personnel.

Despite these facts, and perhaps because the Chesapeake Bay has long been the center of the Nation's oyster industry, with a significant number of individuals dependent upon the industry for a livelihood, there has been a considerable amount of effort directed towards oyster research in this area, by federal, state and, more recently, private groups.

OYSTER CULTURE

Research in various aspects of oyster culture, with particular emphasis upon problems in the Chesapeake area, is currently being undertaken at the Bureau of Commerical Fisheries Laboratory at Oxford, Maryland; at the Chesapeake Bay Laboratory (University of Maryland), Solomons, Maryland; and at the Virginia Institute of Marine Science, Gloucester Point, Virginia. Additional research has been undertaken at a private facility on the Rappahannock River near Urbanna, Virginia, with funds made available through the Economic Development Administration.

Aside from investigations on oyster mortality and disease, particularly during recent years and since the advent of MSX in the Chesapeake Bay in 1959, research on improved methods of culture has been directed in the following areas:

a) Collection of oyster spat, and culture of the juveniles to maturity, by suspension methods.

b) Culture of oysters in artificial ponds.

c) Raising oysters on supplementary, artificial (as opposed to natural) foods.

d) Production of seed oysters by hatchery methods, including production of "cultchless" oysters.

Raft culture experiments were initiated to determine a) whether shell cultch suspended from the surface might receive more intensive sets than shell spread in traditional fashion on the bottom, and b) whether oysters in the Chesapeake region grew significantly faster and were of higher quality, i.e., higher percent solids of meat, than their counterparts on the bottom. Although the biological results were generally favorable (Shaw, 1968), raft culture in the Chesapeake is not, as yet, a totally satisfactory method of oyster production.

Newly-set spat on strings suspended from the surface are, in certain parts of the Chesapeake, extremely vulnerable to attack by the predatory flatworm, **Stylochus ellipticus** (Dr. Robert Hanks, Dr. Jay Andrews, personal communications), particularly when less than 10 mm in length. It has been observed that this predator completes its motile larval period and undergoes metamorphosis at a time similar to that of the oyster, and is particularly destructive to newly-set oysters. Possible methods of control include transfer of shell, upon which spat have become attached, to **Stylochus**-free areas; dipping of the shells, prior to attachment of spat, in Polystream, which reputedly is toxic to the flatworm but not to the larvae; and dipping the strings of shell in a brine solution, a procedure that again is more injurious to the worm than to the oyster. The practicality of any of these alternatives may, on a large scale, be limited as a result of labor and expense.

Shaw (1968) has determined that, despite the fact that, in terms of water temperature, the Chesapeake Bay has a longer growing season for oysters than New England, i.e., six months as opposed to three months, total annual growth increment is approximately the same for both areas. He has attributed this to the comparatively reduced tidal amplitude in the Chesapeake, with subsequent limitations upon food supply during each tidal cycle. Although shell growth was not as high as expected, it was found nevertheless that oysters cultured by suspension had an appreciably higher solids content than did those cultured in traditional fashion on the bottom. Despite this advantage, however, raft culture is relatively expensive in terms of materials and the labor involved in raft and shell-string construction. To be profitable — using current methods — the grower should expect to receive $10.00 for each bushel produced, a circumstance that would appear unlikely for the immediate future.

Although fouling may not be as intensive in the brackish waters of Chesapeake Bay as in other areas, it nevertheless presents an additional problem for raft culture. This is particularly true for shell that is suspended as cultch, since the shell may foul with bryozoans or other organisms before the oyster larvae can set.

The use of artificial ponds for oyster culture has also been explored in the Chesapeake area. At the Bureau of Commercial Fisheries Laboratory in Oxford, water is pumped into a series of quarter acre ponds at a rate of 50 gallons per minute. This rate of flow has been found inadequate to sustain appreciable populations of oysters, whose rate of growth and condition index in the pond environment has been found to be distinctly inferior to that of oysters grown in nearby natural areas. As a means of providing supplementary food, algae cultured in large tanks is pumped into the ponds containing oysters. The results of this experiment have not been determined as yet.

An interesting series of experiments on the artificial feeding of oysters, as a means of improving their meat quality and hence their market value, has been undertaken at the Virginia Institute of Marine Science at Gloucester Point, Virginia. Of the various synthetic (as opposed to natural) foods tested, only carbohydrates, in the form of various cereals, have produced meaningful results, and in general the resulting benefits have been associated with increase in meat weight rather than in shell length. It is apparent that a diet predominantly carbohydrate in nature lacks the necessary amino acids, vitamins, minerals or other substances that promote shell growth.

Best results have been obtained by autoclaving finally-ground corn meal or wheat flour, or a dextrose solution, so that the particles are reduced to colloidal form. If the food solution has a dextrose concentration of two to three parts per million, for example, optimum flow rate is one liter per minute for eight oysters averaging two inches in length. Oysters may fatten readily on this diet, provided as a continuous flow, particularly during fall when they are generally in poor condition after spawning.

The major problems encountered in artificial feeding have been a) anaerobic conditions developing in the feeding tanks as a result of excessive food, b) marked seasonal differences in results, c) difficulty in distributing the food homogeneously so that all oysters receive an adequate supply, and d) the considerable water volume requirements. (Synthetic foods have not produced satisfactory results in the absence of continuously flowing water.)

Quite recently (Hidu et al., 1969), investigations on the technical and economic feasibility of producing oysters by hatchery methods have been initiated in the Chesapeake Bay area, i.e., Chesapeake Bay Laboratory at Solomons, Maryland, and Virginia Institute of Marine Science, Gloucester Point, Virginia. At the former facility, the major purpose of current research is to determine the feasibility of oyster hatcheries in areas of low salinity, that is, where the salinity may range from 10 to 20‰. The criteria for an economically justifiable hatchery would be a) inadequate local supply of seed oysters, b) relative scarcity of predators and disease, c) availability of suitable hard bottom for culture, or alternatively, possiblities for raft culture, and d) sufficient natural food in the water supply to make unnecessary the expensive culture of algal food for larvae and juveniles. The rationale for oyster hatcheries in Maryland is that this State has relied to a certain extent upon Virginia as a source of supply of seed oysters, and this source is no longer considered dependable.

At the Solomons facility, adult oysters have been conditioned and induced to spawn from February to September. In the early part of the season, the oysters are held in running water, heated to 24°C, for a period of six weeks; this is sufficient to bring the oysters to spawning condition. As reported by Hidu et al. (1969), water temperatures are then elevated to 30°C within a half-hour period. Periodically, suspensions of gametes, stripped from mature gonads, were added to the culture. This treatment was continued for six to eight hours, if necessary; oysters that failed to spawn during this period were returned to the conditioning trays. During the conditioning period, water flow should be maintained at a minimum of one-half liter per minute per one dozen oysters. During the late spring, summer, and fall, spawners were obtained by holding wild oysters, obtained from the field, for at least a week at 20° - 22°C. During a period of one to two weeks, sufficient gonad material develops to allow spawning when the temperatures are subsequently elevated.

Oyster larvae are handled in the following manner. Fertilized eggs are held at densities of 15 - 30 per ml, in water filtered to one micron and warmed to 24°C, for a period of two days. The larvae are then thinned to densities of 10 per ml of culture water, at temperatures ranging from 24° to 30°C. (At the higher temperatures, larval development proceeds more rapidly, but incidence of bacterial infection is higher. The antibiotic Combistrep, added at concentrations of 200 parts per million, has been found to reduce infection.) The water is changed daily, by passing the larvae through a series of fine-meshed screens that remove larger potential predators, and the larvae are then returned to containers filled with warmed seawater passed through a five-micron bag filter. Combistrep is provided at concentrations of 200 parts per million at each water change. Under this regime, and at culture temperatures of 24° - 25°C, approximately 18 days are required for the oysters to complete their larval period and undergo metamorphosis.

Despite the handling requirements involved in daily water change, this method has one very distinct advantage over methods described for the Long Island Sound hatcheries, i.e., the apparent lack of need for providing supplementary food for the larvae, as in the form of cultured algae. Obviously, whether or not this system is workable on a large scale would depend upon the location of the hatchery and the nature of the water available to it. Furthermore, the above data suggest a relatively slow rate of larval development in the absence of supplementary food.

At the Gloucester Point research facility, more emphasis has been given to the culture of algal foods for larvae, including **Monochrysis, Isochrysis** and **Dunaliella euchlora.** These species are raised in five-gallon carboys and maintained as continuous cultures for as long as three months. **Monochrysis** cultures have attained densities of four to six million cells per ml, and **Isochrysis,** two to three million cells per ml. More recently, consideration has been given to methods of culturing certain protozoans as food.

Growth of oyster larvae has been found to be highly erratic at Gloucester Point. The food value of the natural water reportedly varies from week to week, hence the greater dependence upon cultured food. Some difficulty has been encountered in inducing parent oysters to spawn. However, this program to date has not been concerned with large-volume production but rather with experimental production of stock resistant to MSX.

Personnel at Gloucester Point have also been interested in methods of obtaining "cultchless" oyster spat. ". . . Larvae placed within fine plastic netting or screens are forced to set on threads of the net from which they are easily washed off with jets of water. Sand grains or fine particles of shell are also acceptable to the larvae". However, despite the apparent ease with which cultchless oysters may be obtained, the problems in handling the juveniles subsequent to metamorphosis are as yet formidable. As Andrews and Mason (1969) state, "Chesapeake Bay has a relatively large supply of wild oysters for harvesting and transplanting, hence hatcheries and "free" spat are probably not competitive here but may be in places such as Long Island, N.Y.".

At present, it is difficult to foresee an economically viable hatchery operation in the Chesapeake area, pending a sharp increase in the market value of Chesapeake Bay oysters. At the present time, growers may obtain seed oysters from natural sets for as low as $0.60 per bushel, and, as indicated earlier, the cost of producing a bushel of seed oysters in one of the large commercial hatcheries in Long Island Sound apparently falls between $5.00 and $10.00 per bushel. Hatchery costs can certainly be reduced if natural seawater is employed as a food source, but it would seem highly doubtful that cost reduction would be sufficient to justify a large-scale oyster seed production facility.

The South Atlantic States

THE INDUSTRY

The oyster industry of the South Atlantic States, which consist of North Carolina, South Carolina, Georgia and the East coast of Florida, has remained relatively stable during the past forty years, although total production around the turn of the century was approximately double what it is today. Approximately three and one half million pounds of oysters were produced in this region in 1966, with a total dockside value of about one and one half million dollars. The average value per pound was 43 cents, or about two-thirds that of oysters produced in the Chesapeake Bay. The leading producer presently is South Carolina, although both North Carolina and Georgia out-produced South Carolina near the turn of the century.

The following observations on the North Carolina oyster industry are perhaps pertinent to the industry in many parts of the country: "It has already been noted that the increases in United States fishery production have occurred chiefly in the mass production, mechanized fisheries. The mollusk fisheries have depended on extensive use of human labor to dig, dredge, or tong the product from the mud or water, and it has been only recently that power dredges have been introduced or significantly improved; until 1948, power propelled craft were prohibited in North Carolina for dredging oysters. A great deal of hand labor is used to cull oysters and to shuck them, both in plants and restaurants, little of which has been successfully mechanized. The increased cost of production occasioned by increased labor wages could be aggravated by diminished yield per day's work on depleted natural rocks." (Taylor, 1951).

The maximum price a North Carolina fisherman may expect for his product is $5.00 per bushel. The price is lower in the other South Atlantic States. Although 5,000 acres of bottom are privately leased in North Carolina, the fishery is for the most part a public one in this area. Only a very small fraction of the oysters produced are sold for the half-shell trade, the great majority being shucked and canned, or sold as raw shucked oysters. Most of the oysters produced in North Carolina are sold to, and shucked in, Virginia shucking houses.

Because of the low market value for local oysters, there is relatively little incentive to farm oysters on a systematic basis. Efforts to do so on a private basis would be resisted by local fishermen or thwarted in many counties by local regulations. This problem is compounded by pollution of once-productive beds, heavy siltation of beds particularly after freshets, and generally poor management. In this regard, natural beds have been depleted over the years, with relatively little effort to restore them by planting cultch, i.e., returning shells from the shucking houses to the beds.

In South Carolina and Georgia, the great majority of the oysters grow intertidally. According to Linton (1968), oyster rarely survive or at least are in poor condition when established below the low tide mark, as a result of heavy infestation by parasites, i.e. the boring sponge, **Cliona sp.,** and oyster crab, **Pinnotheres ostreum,** and predation. In South Carolina, the yield per bushel varies from 25 to 30 ounces of meat, which is extremely low as compared with oysters from more northerly latitudes, e.g., 7 pounds per bushel.

One of the reasons for the poor yield is overcrowding and hence competition for food on the oyster bars. Unlike the picture described for the States further to the north, reproduction in the southern states may be so intensive as to create a problem of quality, i.e., oysters that are suitable only for canning. Lunz (1954) reported that spatfall in South Carolina was almost continuous from May to October, and estimated that it was roughly three to four times as intensive as in Connecticut or Maryland.

OYSTER CULTURE

In view of the large amount of potentially suitable growing area and the high reproductive potential, it is not surprising that major emphasis in research in recent years has been upon methods of rearing the spat to marketable size as rapidly and safely as possible, with maximum use of the natural environment. Methods of culture that would involve a distinct increase in cost production, e.g., hatcheries, would have little justification. Efforts have been made at the Bears Bluff Laboratory, near Charleston, South Carolina, to culture oysters to maturity in artificial ponds, but this has been done in conjunction with other organisms of marketable value, e.g., shrimp, finfish, etc.

In recent years research interest in North Carolina and Georgia has focussed upon culturing oysters by suspension methods, and, in the former area, upon developing a suitable artificial cultch. In North Carolina, the industry is presently so limited that, for one interested in expanding his oyster operations, obtaining a sufficient amount of oyster shell as cultch would present a problem. In certain areas, marl has been used with some success as a substitute for shell.

In both States, fouling of shell strings presents the most formidable obstacle to suspension culture methods. In North Carolina, growth may be extremely rapid, with oysters attaining three inches in length within one year after setting. Using strings five feet in length, 150 bushels of oysters have been cultured from a platform measuring 30 feet by 30 feet. As a method of avoiding fouling, particularly by barnacles and ascidians, the strings are exposed to air for a period of four hours, two or three times each week. Although this procedure has proven successful on an experimental scale, it would appear doubtful that the present local market price for oysters would justify the labor required in a large operation.

In Georgia, various problems have been encountered in experimental raft culture operations. Oysters are heavily fouled with barnacles, bryozoans and sea squirts, to the extent that the juveniles may be smothered. Destruction of wooden rafts by ship worms is severe, and styrofoam may be damaged by the stone crab, **Menippe mercenaria.** A high current velocity with heavy silt in the tidal creeks tends to reduce growth rate, and the spat may be preyed upon by a variety of fish and crustaceans. Again, the conclusion has been (Linton, 1968) that suspension methods of culture, although showing promise, are not presently economically justifiable in this region where oysters command such a relatively low price.

In short, the economic incentive to undertake research into more sophisticated methods of oyster culture is presently lacking in the South Atlantic States. It is possible, as Linton (1968) suggests, that increasing demand for oysters may elevate prices to the point that a greater technology would be justified. (In the past, oysters from the southern states have been planted in Long Island Sound and in the waters of Cape Cod, in the hope that they might survive and assume the favorable appearance and flavor required for the helf-shell trade. Unfortunately, survival through the New England winters has been negligible.)

The Gulf Coast States

THE INDUSTRY

Oyster production in the Gulf States, which would include the West Coast of Florida, Alabama, Mississippi, Louisiana and Texas, is unusual in comparison with that of the regions described above, in that volume has remained quite stable since the turn of the century to the present day. In 1963, Louisiana was the Nation's leading oyster producer (11.5 million pounds), and today nearly half this country's oysters are produced in the Gulf of Mexico. The value of the Gulf States oyster, on the other hand, is rather low and comparable to that of the South Atlantic States oyster. In 1966, the dockside price for oysters in Mississippi averaged 27 cents per pound. The average dockside price for the five States in that year was 38 cents per pound.

(In Louisiana, oysters presently sell for $3.00 per bushel; in Florida, the price to the fisherman is more apt to be $3.50 per bushel. These figures should be compared with the prices of $22.00 per bushel in Massachusetts, $18.00 per bushel in Connecticut, and possibly $8.00 per bushel in Delaware Bay.)

Although volume of production in the Gulf States is considerable, it is generally believed that it has realized only a fraction of its potential. In contrast with the industry in Long Island Sound, which is to a large extent vertically integrated, the industry here is disorganized, with little emphasis upon marketing techniques and quality control. By and large, the wholesalers are ex-fishermen with little experience in marketing or in contractual arrangements. Because oysters are highly perishable in warm climates, the wholesaler is very often at the buyer's mercy, since he must dispose of his product. The buyer, on the other hand, may argue that, since he cannot depend upon the wholesaler for either quality or quantity, he cannot establish more favorable prices. In Florida, for example, where there is a high and growing tourist demand for oysters, the value of local oysters remains depressed, even though native gourmets may argue that the Gulf oyster is at least equal, and perhaps superior, in quality to its northern counterpart.

Oysters produced in the Gulf are either shucked and sold fresh, steamed opened and canned, or sold in the shell for the half-shell trade. Roughly 70 to 80 percent of the oysters grown in Louisiana are canned, and may be bought by processors from Alabama, Mississippi and even Virginia. Only oysters of exceptional quality are sold to oyster bars for consumption in the shell. A significant percentage of total production is shucked for packing, and an increasing worry to the industry is the inability to obtain the necessary labor. Because of its low economic and social status, the job of oyster shucker is becoming increasingly difficult to fill.

Most of the oysters harvested in Florida are tonged or hand-picked from public reefs, the center of the industry being Apalachicola Bay. The great percentage of oysters produced in Alabama, Mississippi and Texas are also harvested from public grounds, there being the usual public resentment regarding private leases in these States. (At the present time, there are only 50 private lease-owners in Texas, of which only 10 are currently active. In Alabama, 978 acres are under lease.) In Louisiana, on the other hand, almost all of the oystermen have their own private beds, ranging in size from 100 to 1000 acres. At the present time, there are about 1000 private lease-owners in Louisiana, with a total of 120,000 acres under lease, and an additional 30,000 acres now under survey for leasing.

In addition to the socio-economic problems referred to above, the Gulf's oyster industry is faced with various environmental problems as well. Periodic hurricanes, with resulting damage to oyster beds, have caused sharp periodic fluctuations in production, particularly in Louisiana. Recent diversion of the Mississippi River through the Gulf outlet has allowed intrusion of saline water over previously brackish-water oyster beds, permitting an influx of the Gulf's most serious oyster predator, the conch or drill **(Thais haemostoma).** Various forms of pollution, including domestic sewage and oil spills, have endangered or eliminated once-productive beds. Finally, in most oyster-producing areas of the Gulf, high mortalities occur each year as a result of epidemic diseases, the most generally common of which is attributed to the fungus **Dermocystidium** sp., and, more recently, to a related fungus **Labyrinthulumixum** sp. (Recent investigations indicate that these may be the same organism.)

Since oyster disease has had a pronounced effect upon oyster culture and research programs in the various Gulf States, and in fact upon the structure of the industry itself, certain aspects of the disease are worth commenting upon. In Florida, where mortalities may be as high as 100 percent under certain conditions and in certain areas, the suspected pathogen **(Labyrinthulumixum)** occurs only in waters with salinities in excess of 20°/oo; major kills occur when temperatures are in excess of 30°C, and salinities in excess of 30°/oo, when the animal may be under a certain amount of environmental stress. In Florida, the most critical period for the oyster is during July and August, when such conditions may prevail. Similarly, in Alabama, the lower limits for the pathogen are 20°/oo and 25°C.

In Louisiana, predation by the drill **Thais** and by the drum, a fish capable of crushing the oysters in its teeth, is perhaps a more serious problem than disease. Nevertheless, an oysterman who plants seed oysters on his beds during the fall generally plans to harvest them the following spring, since otherwise there will be a loss of 75 to 90 percent during summer (Waldo, 1962).

In Texas, heavy oyster mortalities are attributed to **Thais** and both to **Dermocystidium** and the so-called Aransas Bay disease. (Aransas Bay, once the leading oyster producing area in Texas, has not produced a single oyster in five years as a result of epidemic disease.) In Texas waters, the organism causing the Aransas Bay disease cannot tolerate salinities under 20°/oo, whereas **Dermocystidium** can cause damage in areas with salinities of 10°/oo or even lower. It has been observed that when the Aransas Bay disease organism appears, **Dermocystidium** disappears completely.

Despite these factors, the Gulf environment is generally favorable for oyster culture. In certain areas, growth may be extremely rapid. In parts of Florida, oysters have grown to a size of five inches in a period of 10 months, although such growth is exceptional. More typically, an oyster becomes three inches in length one year after setting. In Louisiana, oysters cultured on the bottom grow to a size of 3 inches in about 14 to 16 months; these are generally marketed as two-year olds, having a length of four inches. In Alabama, oysters have attained a length of three to four inches in a period of seven months. Such growth is striking in comparison with most other oyster-producing areas, and, where suspension culture techniques have been tested, the difference is even more striking. Favorable growth, coupled with the fact that reproduction is rarely a problem, are two advantages not enjoyed by most other oyster-producing areas.

OYSTER CULTURE

The Florida Board of Conservation is undertaking research in the following areas:

1. oyster nutrition.
2. identification of factors causing epidemic disease in oyster populations.
3. physiological response of oysters under varying environmental conditions, e.g., temperature, salinity, etc.
4. construction of artificial oyster reefs.
5. channeling through existing oyster reefs to improve circulation.

The emphasis clearly is not upon methods of increasing the oyster populations, which is the case from the Chesapeake Bay northward, but rather upon improving the quality of available oysters, as a means of elevating the price, and upon minimizing the annual losses resulting from disease.

The primary purpose of oyster nutrition studies has been to develop methods of increasing the glycogen content of oysters that are in poor condition. At the present time, oysters are of favorable quality only from Thanksgiving to mid-March, since spawning may occur from April to November. Aware of increasing incidence of water pollution from domestic sources, the Board of Conservation is interested in developing a system whereby oysters may be depurated, i.e.. purified of possible pathogenic organisms and thereby made fit for human consumption, and their condition improved simultaneously and within a reasonable period of time.

Preliminary experiments with adult oysters (three to six inches in size) indicated that provision of various algae (**Chlorella, Stichococcus,** ground **Ulva,** ground **Gracilaria, Skeletonema** and various dinoflagellates) had little effect upon oyster condition, i.e., in this case, as reflected by percent glycogen content. When unicellular algae were provided as food, each oyster received roughly 30 million cells per day.

Best results were obtained by grinding various cereal grains to a maximum particle size of 15 u with the majority in the three to five micron range, and making up stock solutions of two and one half gm of cereal per liter of filtered seawater. (As a rule, these solutions were not sterilized, although sterilized solutions reportedly produced favorable results also.) The solutions were added daily to a 250-gallon recirculating tank holding 120 mature oysters, in which the water was changed daily. The food was provided at a rate of 20 grams per 120 oysters per day, or 6 grams of cereal per oyster per day. Since the oysters stopped pumping at excessive carbohydrate concentrations, an effort was made to maintain the concentration at 5 - 10 mg carbohydrate per liter. The rate of water flow through the system was 12 liters per minute.

Corn meal and whole brown rice have produced favorable results, as has Quaker Oats Q-bine (a corn meal formula containing various vitamins, amino acids, etc.). Attempts to adsorb glucose to barium sulfate, thereby using the latter as a food vehicle, have not been successful.

The average amount of time required for a poor oyster to improve significantly in condition has been six weeks. During this time, the glycogen content has been observed to increase by as much as 600 percent. It is hoped that, through manipulation of carbohydrate concentration and water flow rate, the average time required may be reduced to three weeks. If this procedure is determined to be economically feasible on a large scale, it is hoped that the Florida oyster may eventually become competitive in price with the northern oyster.

With respect to physiological investigations, the current major objective is to define the optimum temperature and salinity levels, as well as the maxima and minima, for growth. The applications of this study would be determination of the most favorable natural beds for culture, where disease may be avoided by conditions of temperature and salinity, and development of artificial feeding and depuration systems in which oysters may be fattened and cleansed simultaneously.

In Alabama, limited investigations on the culture of oysters in ponds and from rafts have been undertaken. Most of the waters in Alabama are shallow and unprotected, and strong winds combined with interference by humans have cast some doubt on the feasibility of raft culture (May, 1968). In Alabama, oysters normally sell for a maximum of $10.00 per barrel (three bushels to the barrel); preliminary experiments indicate that it costs roughly $27.00 to produce a barrel of oysters by suspension methods. Nevertheless, despite the fact that the oyster industry in Alabama is largely a public fishery, with local resentment to private leasing, experiments in raft culture are continuing.

At the present time, little oyster research is being undertaken in Louisiana, at least with respect to methods of culture, although much effort has been devoted to natural seed production. In the past, attempts have been made to culture oysters in artificial ponds as a supplementary crop to shrimp. In these quarter-acre ponds, the construction of which has been described by Broom (1969), oysters have been stocked at densities of one per square foot. These experiments were concluded, however, when high water temperatures resulted in excessive mortalities.

The oyster grounds of Louisiana are felt to be too shoal for effective raft culture operations. However, consideration is being given to the feasibility of diverting fresh water into saline areas, or damming off estuarine areas, as a means of creating brackish water environments free of oyster drills and disease.

In Texas, where disease is perhaps the major concern in the industry, two separate approaches are being undertaken. One involves initiation, by a private group, of an oyster hatchery program, its purpose being to develop an oyster strain that is resistant to local disease and to culture these oysters in coastal ponds. This program is in the preliminary stage, and no data are available.

In Palacios, Texas, the Parks and Wildlife Department have recently constructed a series (21) of artificial ponds, ranging in size from one quarter to four acres in surface area. These ponds are filled by pumping water through filter bags to remove potential predators and competitors. Shrimp, crabs and certain finfish will be cultured in these ponds in addition to oysters. Fertilizer — in the form of commercial-grade 12-20-6 plus urea — has been added to certain of these ponds to promote growth of algal food. To date, data on the results of these experiments are not available.

At the present time, the dockside price for oysters in Texas is about $2.00 per bushel, or slightly more. The combined factors of reduced price plus restrictions on private leasing are not particularly conducive to extensive research on methods of oyster culture.

In summary, the picture regarding oyster culture in the Gulf States is similar to that of the South Atlantic States. State efforts for the most part are confined to relaying oysters from polluted to clean areas, and to provision and maintenance of seed oyster collecting areas. In these regions, considerably more research effort is expended upon the culture of shrimp, which is in high consumer demand and is of considerably greater economic importance than the local oyster industries.

The Pacific Coast States

THE INDUSTRY

The oyster industry of the Pacific Coast States differs from that in the Eastern and Southern States in that it is based almost entirely upon the Pacific, or Japanese, oyster (**Crassostrea gigas**), to a limited extent upon the native, or Olympia, oyster (**Ostrea lurida**), and virtually not at all upon the eastern oyster (**C. virginica**). In addition, relatively recent efforts to culture the European oyster (**Ostrea edulis**) in this country have been concentrated for the most part on the Pacific Coast. Finally, the Pacific Coast oyster industry is, for all intents and purposes, a private fishery undertaken on privately leased beds.

If the oyster industry has shown a steady decline on the Atlantic Coast and has barely managed to hold its own along the Gulf Coast, its long-term trend on the Pacific Coast has been favorable. Less than one million pounds of oysters were harvested on this Coast in 1930, as compared with 11 million pounds in 1940, eight million pounds in 1950, and over 11 million pounds again in 1960. Latest statistics (1965) indicate a slight decline in production, to slightly over nine million pounds, and there is evidence that increasing imports of **C. gigas** from Japan have had an unfavorable effect upon the local industry, where production costs are higher.

At the turn of the century, the only species produced were **C. virginica** and **O. lurida.** (In 1904, slightly over one million pounds of **C. virginica** and over two million pounds of **O. lurida** were produced, as compared with eight thousand and forty thousand pounds, respectively, in 1965.) Production of **C. gigas,** which according to Steele (1964), was first successfully introduced to the Pacific Coast in 1919, did not begin until 1922; by 1931, its volume exceeded that of the other two species combined.

The history of the industry will be quickly reviewed. Prior to the turn of the century, California was the leading oyster producer on the West Coast, and the product was the Eastern oyster, brought from the Atlantic Coast to be planted in areas such as San Francisco Bay and, after an interval of time, harvested for market. These oysters did not reproduce locally, due to the comparatively low water temperatures. In 1899, over two and one half million pounds of Eastern oysters were harvested from California waters. By 1905, the ecology of San Francisco Bay, evidently as a result of pollution and dredging and filling of the shoreline marshes, had become so altered that the transplanted oysters failed to grow and, in certain cases, survive. 1910 marked the last year that oysters were planted in the Bay; by 1930, the Eastern oyster industry had virtually disappeared (Barrett, 1963), although a limited number are still planted in, and harvested from, Tomales Bay. Demand and ready markets for high-quality oysters had, however, been established.

The native oyster (O. lurida) industry followed a similar path, but for somewhat different reasons. This species is capable of reproducing at much lower temperatures than either **C. virginica** or **C. gigas**, and at one time natural populations were abundant throughout much of the Coastal Pacific Northwest. Being sensitive to excessive heat or cold, it cannot be cultered intertidally — as can the two species of **Crassostrea** — so that the oyster growers developed a system of dikes whereby the oysters were always covered by water, even at extreme low tides. The decline in abundance of this species has been attributed in part to the discharge of sulfite waste liquor from pulp mills in Puget Sound and elsewhere, but its relatively slow rate of growth — it requires three to five years for this species to reach one and one half to two inches in length — combined with the labor involved in its culture, harvest, and processing, have tended to discourage the industry. The price of this species is high by volume; a gallon of shucked oysters brings $35.00 to $40.00, but it requires 1200 to 1500 native oysters to make up a gallon (as opposed to 50-200 Pacific oysters, or 150-250 Eastern oysters). In any event, production of this species has declined steadily since the turn of the century, to the extent that it presently comprises less than one percent by volume of total production, and about five percent of total value.

With the introduction of **C. gigas**, the Pacific Coast industry underwent a considerable change. This species is extremely hardy and grows rapidly. In certain areas, it may reach a length of six to seven inches within two or three years. In most areas of the Pacific Northwest, water temperatures never attain the minimum required for this species to spawn, i.e., 20° to 22°C, so that the majority of oyster growers must import their seed from Dabob Bay in Washington, Pendrell Sound in British Columbia, or, traditionally, from Japan.

It should be emphasized that, in contrast to both the Eastern and native oyster, the Pacific oyster is not a luxury food, and in fact had considerable difficulty initially in finding market acceptance in the restaurants, hotels and other outlets of California, Oregon, and Washington. In 1966, the dockside value in California was 28 cents per pound, or about the same value as that of oysters produced in Mississippi. Whereas the majority of Eastern and native oysters produced locally are consumed raw, as cocktail oysters or in the half-shell, the great majority of Pacific oysters are cooked, largely because of their strong flavor and, for some people at any rate, unappetizing appearance. (The shell of the typical **C. gigas** is apt to be large, coarse and misshapen, and the margin of the mantle is usually dark. The strain of **C. gigas** known as the Kumamoto oyster, because of its origin from this southern region of Japan, is smaller, more attractive in appearance, and more suitable for the cocktail trade.) Only a small percentage, therefore, are sold in restaurants, the majority being marketed to the housewife freshly shucked, canned, frozen or smoked. In this form, it is competitive with other foods not necessarily classified as luxury.

Certainly one of the major problems confronting the industry is foreign competion. As indicated earlier, oyster imports have greatly increased during the past two decades, particularly the canned variety, and it is the Pacific oyster industry that is being effected the most. The Pacific Coast oyster grower has difficulty in competing with the Japanese, where labor is cheap and particularly since he must, in most cases, purchase his seed oysters.

Another major problem is that of obtaining oyster seed. Even though significant quantities of seed oysters are collected each year in Dabob Bay, Pendrell Sound, and, to a less frequent extent, Willipa Bay in Washington, more than fifty percent of the seed planted each year is purchased from Japan. This seed, delivered by the case, cost $3.50 per case in the early 1930's, slightly over $9.00 per case in 1961, and, at the present time, $18.00 per case, F.O.B. Washington ports. In some instances, the survival of the seed on the beds is extremely low, as a result of poor handling in transit, siltation, and predation.

Of added concern to oyster growers is the increasing incidence of oyster mortality, for reasons not clearly identified (Westley et al., 1967). Mortalities have been linked with blooms of the armored dinoflagellate **Ceratium,** with waste discharge from pulp mills, and with possible disease, and with the parasitic copepod, **Myticola.** Reportedly, seed production in Japan has declined recently for similar reasons.

The major oyster predators in the Pacific Northwest include the bat stingray **(Myliobatis californicus),** which occurs primarly in California and is fenced off from the beds by poles driven into the ground; the oyster drill **(Ocinebra japonica),** which was accidentally imported from Japan; the rock crab **(Cancer productus);** and ghost shrimp, which, as a result of burrowing, may soften the grounds sufficiently to make them uninhabitable for oysters.

As indicated earlier, on the Pacific Coast the industry is almost entirely private. In California, ground is leased by the State for $1.00 per acre, plus a yield tax of one cent per gallon of oysters produced. In Oregon, the rental is $2.00 per acre, with a yield of five cents per gallon. The situation is considerably more complex in Washington, where leasing fees may vary from area to area. In any event, the fact that private ownership of oyster grounds is traditional is reflected in the comparatively progressive nature of the industry in this area.

At present there is only one commerical hatchery operation in the Pacific Coast: Pacific Mariculture Inc., in Pescadero, California. Unlike the hatcheries of the East Coast, which serve as a source of seed oysters for the hatchery owners' beds, this industry supplies seed oysters of various species—including **C. gigas, C. virginica** and **O. edulis** — to other members of industry, not only on the West Coast but on the East Coast and in Europe. Although the operation of this facility will be described in greater detail below, it should be mentioned here that emphasis has been on the production of "cultchless" oysters, a concept that was developed initially at this facility and later modified by other investigators on the East Coast. Pacific Mariculture sells its single oysters, averaging three to four mm in size, for a current price of $3.00 per thousand; the price is slightly higher when the oysters are sold in smaller lots.

One oyster producer in California purchases seed oysters from four sources of supply: Pacific Mariculture, Dabob Bay (Washington), Pendrell Sound (British Columbia), and two different suppliers in Japan. Dabob Bay oysters are sold by the string, each string holding 100 shells, and each shell having 10 or more oyster spat; as such, the strings are sold at $1.75 each. Pendrell Sound seed are also sold by the string, with a current price of $1.60 per string delivered to Seattle. These strings are 10 feet long, carry 200 shells, and the average spat count per string is 10 thousand. If the oyster seed are purchased from Japan, it is either by the case

($15.00 to $18.00 per case, each case holding 15 to 30 thousand seed) or by the shell (one dealer sells for 8 cents per shell, with 15-20 spat per shell).

In the few seed-collecting areas of the Pacific Northwest, and for that matter in Japan as well, oyster spat are normally collected by threading heavy (12-gauge) galvanized wire through a series of C. gigas shells, through which holes have been punched, and, when larvae are abundant, suspending the shell strings from rafts or racks. (In Willipa Bay, where good oyster sets are obtained on an irregular basis, the strings are usually laid horizontally on intertidal racks.) Typically, the shells are punched by machine, with a five-ton metal puncher modified for this purpose. As the shells are punched, they slide down a tubular "needle" to which the galvanized wire is attached. The occurrence and abundance of the larvae, and hence the most appropriate time for suspending the shell, is usually determined by State (Washington Department of Fisheries) or Federal (Fishery Research Board of Canada) personnel.

The majority of oyster growers culture their oysters on the bottom, most frequently in intertidal areas. (Unlike the native oyster, the Pacific oyster is extremely hardy and can withstand prolonged exposure out of water.) The oysters may be harvested by hand, fork, or, when the tide is high, by dredge. It usually requires three to four years for oysters grown on the bottom to mature to marketable size, with maximum growth occurring during the warmer months of the year. A good average yield is 1,000 bushels of oysters per acre every three years.

In certain areas, suspension methods of culture are employed, with striking results. One grower in California, using both racks and rafts from which he suspends his shell strings, claims a production figure of eight to nine thousand bushels per acre per year, which is equivalent to eight to nine thousand gallons per acre per year. In this particular area, the water depth averages six feet; each rack is 12 feet long, is constructed of pressure-treated fir, and may hold 60 strings. Each string holds 18 C. gigas shells, separated from one another by five and three-quarter inch plastic tube spacers to prevent overcrowding of the oysters. The major problem is that of fouling, particularly by mussels and barnacles, and usually juvenile oysters are not suspended until the larval period of these fouling organisms has terminated. Aside from fouling, this producer feels that sufficient oyster food is the limiting factor in production and is attempting to accelerate growth and improve oyster quality through large-scale fertilization experiments.

One grower in Washington uses rafts as part of his growing operations. Each raft, 150 in number, is 16 by 30 feet in dimension and is constructed of styrofoam logs tied together with wooden framing to form a rectangle. Fir poles are laid horizontally across the open rectangle, from which are suspended 10-foot strings bearing the shell with juvenile oysters. After one year, certain of the oysters are harvested as cocktail oysters; the remainder are stripped from the wire and planted on the bottom, to be harvested in subsequent years. Each raft supports 200 strings, and each string carries at least one bushel of oysters. On this basis, oysters are being cultured at an approximate density of one-half bushel per square foot. Although fouling in this area is extremely heavy — the strings are covered with tunicates, anemones, sea urchins, scallops and sea cucumbers as well as oysters — and competition for food is felt to be limiting, both growth and survival rates are nonetheless greatly improved in comparison with bottom culture. (Although this particular grower has experimented with cultchless oysters, holding them in fine-meshed trays attached to the rafts, fouling is so excessive that growth has been poor, and the practicality of culturing free oysters is in this case limited.)

With the exception of the small percentage of oysters sold for the half-shell trade — in certain restaurants, these are known as Quilcene Bay oysters and are simply stunted C. gigas — the oyster grower usually shucks his oysters immediately after harvesting. Since the typical C. gigas may spawn in the warmer areas — even though the larvae generally fail to survive — its condition during the summer months may be inferior. The Kumamoto oyster, however, never spawns, and is in good condition all year round. One producer expects $8.00 per gallon of fresh shucked oysters, each gallon containing about 100 individual oysters. (More typically, his oysters are sold in 10-ounce jars, at 60 cents per jar.) Kumamoto oysters, favored as cocktail oysters, average 600-800 oysters per gallon and sell for $35.00 per gallon, or almost the same price as native (Olympia) oysters. (The latter variety average 1200-1500 per gallon and sell for $35 to $40 per gallon.)

One oyster grower supplements production of market oysters with oyster seed production. He is informed by State biologists when spawning has occurred in Dabob Bay, and of the density of the larvae. At a suitable time, 30,000 strings (100 shells to a string) are suspended, either from rafts or from intertidal racks. (He pays 20 cents for hand-construction of each string.) In four years out of five, he may expect a set of 10 spat per shell or more, and each string, delivered in the area, costs $1.75 to the buyer. As a rule, the seed oysters are not delivered to the buyers until the spring following the set, i.e., when the oysters are nearly a year old. This producer may rent space on his racks to other growers, who make up their own strings, at a rate of 50 cents per string.

Although one bushel of C. gigas normally will produce one gallon of meats, valued at anywhere from $6.00 to $8.00 depending upon season, the value of the unshucked oyster is considerably less. Harvested but unshucked, a bushel of Pacific oysters has an approximate value of $3.50 to $4.00, which is about one-fifth the value of the half-shell oyster of the East. For this reason, a certain amount of interest has developed in establishing a market, on the Pacific Coast, for the European oyster (**O. edulis**), which would be sold in hotels and restaurants as a luxury item and take the place of the Eastern oyster (**C. virginica**), which is still in demand when available on this Coast.

In Morro Bay, California, one company is concerned exclusively with the production of this species (**O. edulis**). The oysters are obtained as free seed, three to four mm in size, from Pacific Mariculture Inc. and held initially in fine-meshed trays on a pier through which water flows constantly. When these oysters have grown to roughly one inch (25 mm) in size, they are transferred to trays, measuring three by eight feet, suspended from rafts. The trays are stacked in tiers, three trays to a tier. It is estimated that oysters may be cultured to maturity in this manner at densities of 100 oysters per square yard. Growth proceeds even though the oysters are stacked upon one another, although very little growth occurs during winter.

It is estimated that marketable oysters may be produced in this fashion in slightly over two years. Natural predation, particularly by the stingray, is virtually eliminated, and the oysters develop shapes suitable for the half-shell trade. In this particular Bay, where water temperatures range from 10° to 15°C, fouling is greatly reduced. Problems encountered by this method of culture here include public antipathy to the rafts themselves; darkening of the oysters' gills, for reasons which are unknown but which tends to reduce their market value; and tendency of the oysters to develop fragile growing edges on their shell, which again reduces their half-shell quality. Added to these problems is the fact that **O. edulis** may ripen and spawn locally and therefore is marketable only during part of the year, whereas **C. gigas** produced locally may be marketed all year round. (In Morro Bay, water temperatures are too cold for the latter species to spawn.) In spite of these difficulties, it is hoped that a ready market may be established for this species, and that it will bring a price superior to that of Eastern oysters shipped from the East Coast.

As indicated earlier, the great majority of oysters produced on the Pacific Coast are **C. gigas** grown on the bottom in relatively primitive fashion. The chief centers of production are Eureka Bay in California, Tillamook Bay in Oregon, and Willipa Bay and areas of Puget Sound in Washington. In effect, the cost in labor and materials of suspension culture has deterred the majority of oystermen, as has public antipathy, even though growth and survival rates of oysters cultured in suspension are clearly superior to those of oysters cultured in traditional fashion. In the opinion of some, it is exceedingly difficult to make a profit in the culture of **C. gigas** unless rack suspension methods are employed, due to losses from siltation and predation and the costs incurred in harvesting. Although there is little question that certain technological developments, e.g., economic methods of operating oyster hatcheries to sustain a supply of seed, would greatly assist the industry, the major problem confronting the industry in future years may be social, i.e., increasing demands upon coastal areas for purposes other than aquaculture.

OYSTER CULTURE

The only commercial oyster hatchery on the Pacific Coast is located in Pescadero, California; this facility has been in operation for approximately five years. At the present time, water is pumped up from the ocean to the hatchery site, where, after passing through a settling tank and a series of bag filters, it enters the hatchery building. The use of ultraviolet light as a sterilization tool has not been found to be necessary at this facility. Within the hatchery, water is heated as required by means of heat exchanger.

As indicated earlier, this operation is presently concentrating upon the production of **C. gigas, C. virginica,** and **O. edulis,** and their sale as free (cultchless) oysters. The method by which these oysters are obtained free of cultch has not been publically disclosed, nor has the method by which the post-larval stages are handled, but in most respects the operation of this facility is similar to that of the hatcheries on the East Coast.

The algal species cultured as food include **Monochrysis lutheri, Isochrysis galbana, Cyclotella nana, Phaeodactylum tricornutum,** and other species currently being tested for their nutritional value. The algae are grown in batches that progress from small flasks to two-liter Fernbach-type flasks, to 30-gallon tanks, and eventually to 200-gallon tanks.

The major problem encountered by this hatchery to date has been inconsistencies in larval growth and survival. This has been attributed on certain occasions to DDT washed by rainfall from nearby farms into the sea, from where it eventually enters the hatchery seawater system. In addition, it has not been found feasible to hold the larvae at higher concentrations than two to three larvae per ml of culture, and, even at this density and at water temperatures of 25°C or higher, 15 to 20 days are required before the larvae undergo metamorphosis.

After metamorphosis, the free juveniles are held and fed, first in the hatchery and later in outdoor trays through which seawater flows continuously. Approximately 90 days after metamorphosis, the oysters are three to four mm in size, at which time they are sold to private growers. This corporation reportedly could sell more oysters than it currently produces; the problem has not been one of demand but rather the inability to guarantee a sustained supply, for reasons given above.

An experimental hatchery has been developed recently in Oregon, operated by the University of Oregon but funded in part by private oyster growers as well as by federal sources. Its purpose is to explore the economic feasibility of hatcheries on the West Coast, with emphasis upon production of **O. edulis, O. lurida,** and **C. gigas,** including the Kumamoto strain, and to undertake breeding studies of potential value to industry. The rationale for this program is largely the fact that the majority of the oyster growers are dependent upon "outside" sources of seed, which may or may not be dependable or, ultimately, economic. In addition, the deterioration of natural environments in the Northwest has led to the belief that oyster culture may become more and more controlled, with increasing use of artificial environments. However, the primary reason is that more than half the oyster seed supplied to the West Coast comes from Japan, and, as a result of the three-week period in transit, more than 90 percent of this seed may die during the first few weeks after planting. Simultaneously, there is the constant danger of introducing unwanted organisms, i.e., predators, competitors and pathogens, as well as possible future unreliability of Japanese supply.

In this facility, no emphasis has been placed upon obtaining cultchless oysters, since it is believed that the heavy siltation characteristic of the estuaries of the Northwest would severly limit their usefulness. Instead, consideration has been given to development of an artificial cultch, such as polyvinyl chloride pipe, which is non-toxic, easily handled, and of practical use in the field.

This hatchery maintains batch cultures of **Isochrysis** and **Monochrysis** as the primary food source. According to Breese (1969), "Pure cultures of algae are maintained under sterile conditions in 250 ml and 2000 ml flasks. Five-gallon carboys are inoculated witth the pure cultures. After an algal "bloom" develops, the carboys are emptied into 100 gallon open tanks where the algae continue to multiply under semi-sterile conditions.[1] Flasks and media are sterilized with an autoclave. The carboys and tanks are sterilized with chlorine. The water used to make the media for the larger containers is sterilized with free chlorine for 24 hours and then dechlorinated through activated charcoal.

"The algal cultures are maintained under fluorescent lights. Algae are allowed to multiply until they reach densities of one to two million cells per ml. These numbers are usually achieved in the 180-gallon tanks seven to 10 days after inoculation from the five-gallon carboys. A Coulter counter is used to monitor density of algal cells in the culture tanks. The larvae, also reared in 180-gallon tanks, are fed three times weekly. Algae are added to rearing tanks to achieve a density of 40,000 cells/ml. The two species are fed at about equal densities of 20,000 cells/ml."

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[1] **Presumably the cultures are still unialgal but are not necessarily bacteria-free.**

No exterior heat exchanger is used in this facility. Where rapid temperature increases are required, electric immersion (Vicor) heaters are employed. Otherwise, the large larval and algal tanks are warmed by fluorescent lighting.

Breese (1969) describes the procedure for conditioning the adults, inducing spawning, and rearing the larvae as follows:

"Elevated temperatures will induce Native and European oysters (genus **Ostrea**) to spawn. These species retain their young in the mantle cavity for about 10 days so elevated temperatures must be maintained throughout the incubation period until the larvae are released by the parent females. The adult oysters are held at 18° to 20°C in standing water until the larvae are released. The larvae are screened from the spawning tank and transferred to the rearing tanks. Water in the spawning tanks is changed daily to avoid contamination from waste metabolites.

"Spawning of native and European oysters can be accomplished from early winter (December) through early fall (October). Natural spawning occurs in summer and the animals are more easily spawned at this time. In spring and autumn, about six weeks are required to induce spawning and release of the young.

"Pacific and Kumamoto oysters (genus **Crassostrea**) do not normally reproduce in Oregon bays because water temperatures remain low in summer. These oysters are brought into the laboratory and held at 20°C in flowing salt water for about 30 days, to condition them for spawning. After the conditioning period, they are placed into recirculated seawater at 25 to 30°C to induce spawning; sometimes it is necessary to sacrifice a mature oyster and add sex products to the water. Once spawning commences, the adults are placed in separate dishes. Eggs and sperm are collected and mixed to achieve fertilization. Embryonic development is allowed to proceed for 24 hours to the shelled stage before the larvae are placed in rearing tanks.

"Female oysters of the genus **Ostrea** produce from 250,000 to 400,000 larvae per spawning while those of **Crassostrea** release 6 to 8 million eggs. Thus, larvae are quite easily obtainable, a fact which favors the production of oyster seed in hatcheries.

"About a half million larvae are placed in each 180-gallon rearing tank. Tanks are constructed of fiberglass and the dimensions are 4′ x 4′ x 2′. They can be drained through the bottom.

"Before water is introduced to the rearing tanks, it is passed through a sand filter and sterilized with ultraviolet light. Water is changed weekly during the free-swimming period by draining tanks through a stainless steel sieve. Larvae are returned to the rearing tank after the new water has been added. Air is introduced to keep water in circulation and to insure a high oxygen content.

"Temperature conditions for rearing the larvae differ somewhat among the species of oysters. Native and European oyster larvae are reared at 18 to 20°C; Pacific oyster larvae at 25°C, and Kumamoto oyster larvae at 28°C. We feed the same number of algal cells (40,000 cells/ML/tank three times weekly) to each species.

"Growth and development of the larvae are monitored by microscopic examination. When the larvae approach setting size (250 to 300 u), which requires two to three weeks in the hatchery, they are screened out and transferred to setting tanks".

One of the major differences between this procedure and that described for the Eastern hatcheries is the relatively low larval density — less than one per ml — maintained in the culture tanks, and the infrequency of water change, at the Oregon facility. It might be argued that, although lower larval mortality occurs in the Oregon system, the spatial requirements for a large commercial facility would be high, and there would be less opportunity for selection against weak or slow-growing larvae. (In one of the Eastern hatcheries, it is estimated that about 90 percent of the larvae are discarded, which are those that have grown sufficiently slowly to pass through sieves of appropriate size.)

One problem experienced at this facility is the eventual appearance of a species of blue-green algae in the algal culture tanks, which is toxic to the food organisms. However, results to date have been sufficiently promising to give rise to the hope that independent commercial hatcheries will be initiated in the area within a few years.

As a possible alternative to hatcheries, personnel of the Department of Fisheries of the State of Washington have undertaken experiments in the production of larvae and collection of spat in large outdoor tanks. Recently, a concrete tank, 80′ x 12′ x 8′ deep, has been constructed for this purpose at the Point Whitney laboratory. As a means of avoiding toxicity from the concrete, a black plastic liner (six mil) will be inserted in the tank. Water will be pumped from a depth of 50 to 60 feet to fill the tank. Since the water will be high in both nitrate and phosphate (ca. 20 and 3 ug-atoms/liter, respectively), it is anticipated that natural planktonic blooms will take place, thereby providing sufficient food for the larvae. During this period the water will be allowed to stand. It is hoped that natural spawning will take place among parent stock placed in the tank; natural larval populations may be supplemented with larvae reared initially in the laboratory.

Although construction of pools is expensive — this particular pool costs $15,000 to construct — this method obviously offers a possible and inexpensive alternative to a hatchery operation. Aside, however, from the possibility that the adult oysters may fail to spawn, other problems have also been encountered in previous experiments. Diatom blooms, in which the total cell count, as captured in a 75 u net, attained one-half million cells per liter, produced effects toxic to the larvae. (The diatoms associated with toxic blooms were **Coscinodiscus sp., Chaetoceros sp., Skeletonema sp.,** and **Thalassiosira sp.**) It is hoped that the occurrence of such blooms may be avoided by shading half the surface area of the tank with black plastic.

Other problems encountered include an extremely high rise in salinity of the tank water, from 26-27‰ to 34-35‰, as a result of evaporation, and excessive fouling of the cultch material, i.e., oyster shell, as blooms occur.

In 1969, 200 adult **O. edulis** will be placed in the tank as potential spawners. Larval **O. edulis** will also be raised in the laboratory to supplement the natural spawning. At this facility, the larvae of this species have been raised successfully at densities of 15 -20 larvae per ml, with little mortality, although high mortalities have been observed at time of setting. Food is added to the culture tanks daily, at a concentration of 100 - 200 thousand cells per ml.

Personnel of the Washington State Department of Fisheries are also engaged in investigations on oyster disease; seasonal occurrence and abundance of oyster larvae, and its relationship to hydrography; predator control and oyster ground improvement; bioassay investigations, using oyster larvae as the assay organism; etc. Investigations were also conducted to determine the effect of feeding starch to oysters as a possible means of improving their condition. Oysters were held in trays through which water flowed at a rate of 10 liters per oyster per hour (Sayce and Tufts, 1967), and starch was added at concentrations of 17, 34, and 68 mg per liter. It was concluded that ". . . . it is possible to inhibit the decline in condition of oysters during July and August and increase their condition during December and January in a laboratory by artificial feeding procedures.", and that oysters fed at a rate of 17 mg per liter fattened as well as did those fed at higher concentrations. In this case, condition was determined by glycogen content. The conclusion drawn was that, although the fed oysters were of significantly better condition than the controls, the difference was not sufficient for a large-scale commercial effort to be practical.

It would seem likely that commerical oyster hatcheries may become more abundant on the Pacific Coast in the near future. In view of the increasingly high cost of Japanese seed, plus the cost and uncertainty of acquiring seed produced in local waters, there would appear to be a definite need for a more reliable local source of supply. However, it would also seem that the current economics of hatchery operation would dictate the production of species of high commerical value, such as the Kumamoto strain of **C. gigas**, or possibly **O. edulis** or **C. virginica.**

British Columbia and Alaska

THE INDUSTRY

In both British Columbia and Alaska, the oyster industry is confined to the production of C. gigas. In neither region has the industry been of particular significance. According to Yancey (1965), only 200 acres or so of tideland have been leased for oyster culture in Alaska, and annual production has never exceeded 550 gallons. All production has been confined to the Ketchikan area, where three years are required for planted juvenile oysters to reach marketable size.

British Columbia produces about 150 thousand gallons of oysters a year, with a total of 30 producers involved in the industry. All of the oyster grounds are privately leased. Unfortunately, because of the steep shoreline characteristic of the area, favorable growing areas are relatively scarce, although it is estimated (D. B. Quayle, personal communication) that potential oyster production could be five times the current volume. Except for the small oysters sold for soup, all oysters produced are consumed in British Columbia — the growers receive $5.00 to $6.00 per gallon — and there is little incentive to expand the industry.

About 40 percent of the oyster grounds have been closed as a result of pollution by domestic sewage. This fact, in combination with the relatively low market price, has deterred efforts towards raft culture, and a commercial hatchery would have little economic justification at present.

Although **O. lurida** is indigenous to this area, virtually none are marketed at the present time. **C. virginica** has been introduced in the past and planted both as seed and adults, but mortality was so high that this was discontinued. Production of **C. gigas,** which until 1930 was extremely limited, increased as natural reproduction occurred in Ladysmith Harbour during the 1930's. A major spawning occurred in 1942 that led to the establishment of a parent population in Pendrell Sound, where consistent sets have been obtained since 1948.

The primary cause of mortality on the oyster beds is siltation, which is particularly detrimental to seed oysters. Major predators include the ochre starfish (**Pisaster ochraceous**), oyster drills (**Ocenebra japonica** and **Urosalpinx cinerea**), and crabs (**Cancer productus** and **C. gracilis**).

OYSTER CULTURE

Methods of raft culture, as they might be applied to British Columbia, have been developed and described by Quayle (1961). Shells holding the spat are threaded on 12-gauge galvanized wire and held apart by twists in the wires every six to eight inches. Thirty shells may be threaded on a string, which is draped over horizontal poles on the raft, 15 shells to a side. The rafts are constructed of logs either chained together or tied together by wooden cross-pieces. Under usual circumstances, the strings might be suspended in February or March, with harvesting beginning in mid-November or December. Quayle has found that, by using suspension methods, the time required for the oysters to reach marketable size is reduced from three years to two and even possibly one, the dark discoloration of the mantle is less evident in suspended oysters; condition is superior, and mortality as a result of siltation and bottom-crawling predators is eliminated; furthermore, the oysters may be harvested regardless of the stage of the tide.

Because of the area's importance for oyster seed production, Canadian biologists have maintained larval monitoring stations at Pendrell Sound. This area is about five miles long and averages over 100 fathoms in depth. Since an adult oyster population became established here during the 1940's, a set failure has yet to occur. This history of successful reproduction, unique for the Pacific Coast, has been attributed to the stability of the water column, resulting from the depth of the water and protection from wind afforded by the steep shores. Surface water temperatures become relatively warm and vary little. Since 1948, the lightest set recorded here resulted in an average of over six spat per shell suspended as cultch.

Shell strings are brought to Pendrell Sound by barge, from Seattle. About 150,000 strings, 10 feet long and bearing 200 shells each, are suspended from rafts when larval concentrations and stage of development are appropriate. As a rule, there is one major spawning. A count of 10-25 straight-hinge larvae per gallon of water sampled is usually indicative of a subsequent intensive set. One advanced-stage larva per gallon usually results in a count of 10 spat per shell. The larval period in this area varies from 14 days to three weeks.

As a rule, high concentrations of small flagellates, reaching densities of 50,000 per ml, occur during the spawning season, and these are apparently the primary source of nutrition for the larvae. According to D. B. Quayle (personal communication), light sets probably result from inadequate amounts of food, which in turn may be correlated with inadequate sunshine.

The strings with spat are collected and transported to various centers by barge, either in the fall following spawning or during the following spring. At the time of sale, there may be counts as high as 10,000 spat per string. These are sold to the buyers at a price of $1.60 per string.

Various kinds of artificial cultch materials have been tested by Canadian biologists. These have included glazed and unglazed tile and discs constructed of laminations of asbestos.

Other than information provided by Yancy (1965), there is little data available on oyster culture in Alaska.

Conclusion

The status of oyster culture in various regions of North America is, in general, a reflection of the economic health and potential for progress of the industry in that particular region. In areas where the industry appears to have the greatest immediate opportunity for progressive development, and where the science of oyster culture has advanced furthest, most of the following conditions appear to hold:

1) There is a high market demand for the product.
2) Local — State, County or Town — legislation is favorable to the private leasing of oyster grounds.
3) The industry is, to a certain degree at least, vertically integrated.
4) Private industry is both willing and able to invest in research.
5) The natural environment, most particularly water quality, remains favorable for oyster culture.

Each of these factors is briefly reviewed with respect to the various regions discussed above.

1. MARKET DEMAND

The market value of oysters declines steadily from the Maritime Provinces of Canada southward to the South Atlantic and Gulf Coast States. One reason for this is the physiological response of oysters to ambient water temperature. Oysters are most desirable for consumption when their glycogen reserves are highest, which is normally during the cooler months of the year. They are least desirable during the spawning season, when glycogen has been replaced by sex cells or when the oysters have spawned out, and the processes of gametogenesis and spawning are stimulated by warm water temperatures. As noted earlier, the spawning season in areas such as Florida may extend from April to November, during which time the oysters have limited appeal. In the Maritime Provinces and in New England, on the other hand, the glycogen content remains high until May (Galtsoff, 1964) and may be restored in September. Therefore, while the oysters to the north are acceptable from September to May, those from the Southern States are in demand only from November through March.

Despite this seasonal disadvantage, it would seem that, during the favorable months of the year, the Southern oyster should be of a quality similar to the Northern oyster and hence command an equivalent market price. However, the majority of Southern oysters are harvested from reefs, bars or "rocks", where competition for food and space may be intense. This condition is of course aggravated by the high reproductive potential of oysters in warmer climates, where overcrowding may be severe. As a result, many oysters of marketable size are misshapen and undernourished, infested with unsightly commensals and parasites, and hence of limited value for the half-shell trade. (In the North, growers separate oysters continually and plant their beds in such a way as to assure favorable shape and quality; obviously, such efforts in a public fishery would be wasted.) In addition, many of the Southern oysters are harvested from waters of reduced salinity, which may impart to them a bland flavor.

Natives to the Southern States may argue that a Southern oyster in prime condition would be as desirable for the half-shell trade as any Northern oyster. However, to ship oysters, in the shell, to the Northern urban centers — Boston, New York, Philadelphia, Chicago, San Francisco, etc., — in quantity would be an expensive proposition, and it is in such centers where consumers are willing to pay high prices for raw oysters. In these areas, the dealers concentrate upon established names as Cape Cod oysters or Blue Point oysters, i.e., oysters with a reputation for quality that, whether true or not, assure ready acceptance.

Within the past decade, producers of soft shell clams **(Mya arenaria)** from the Chesapeake Bay have been able to compete reasonable successfully with Northern producers, primarily because their product was considerably cheaper and, when processed as a fried clam, was not notably different in either appearance or flavor from the supposedly superior Northern variety. However, in the half-shell oyster market, shape and appearance of shell as well as natural flavor are important factors, and it is doubtful whether the average Southern oyster could meet conventional requirements. Even if both shape and appearance were favorable, the brackish water flavor of many oysters from the South, including the Chesapeake region, would be disappointing to the Northern consumer.

Even though the oyster from the Southern States cannot compete successfully with the Northern half-shell variety, it should be possible for them to earn more than 27 to 39 cents per pound to the fisherman (1966 average value for the South Atlantic and Gulf States oyster). To do so would require higher regard for the quality of the product, and greater incentive on the part of the fisherman to supply a superior oyster.

2. PRIVATE LEASES

As stated earlier in this report, it is difficult to conceive of the oyster industry progressing to any appreciable extent in areas where it is based upon a public fishery. According to Staples (1967), the State of Maryland — site of the country's largest public oyster fishery — invests nearly two million dollars each year in subsidizing the industry, with an annual return of only four to eight million dollars. Annual yields from the public grounds average less than five bushels per acre, in contrast with 50 bushels per acre from the few private grounds, which, as explained earlier, are marginal to begin with. (On certain of the private grounds on the Pacific Coast, where suspension methods are employed, yields approximating eight to nine thousand bushels per acre have been reported.)

A public fishery clearly reduces the incentive on the part of the individual oystermen to develop good management and conservation practices, since others who have not devoted the same time and energy are equally free to share in whatever benefits may be derived. Furthermore, any research in oyster culture that is to be of local practical value is restricted to techniques adaptable to a public fishery. In Florida for example, this has taken the form of construction of oyster reefs, and of channelling the reefs in an effort to improve growth rates. Although such programs may be of some benefit, at public cost, the oysterman remains essentially a hunter rather than a farmer.

Staples (1967) has urged research on the use of artificial ponds as a means of efficient oyster culture and also as a means of avoiding the legal difficulties of private ownership in natural waters. American Cyanamid (1969) and Johnson et al. (1968) have discussed and analyzed the possibilities of culturing oysters in completely artificial environments. Biologists in Maryland and Virginia are exploring the economic feasibility of oyster hatcheries in the Chesapeake Bay area. From a purely scientific point of view, these approaches have merit, but they require a substantial economic incentive in order to justify their cost. When the current market price for local oysters is low, as in the Southern and Gulf States, such measures would appear to be of questionable economic justification.

Shaw (1968) and others have demonstrated that oysters of superior quality can be grown in Southern areas, and possibly at reasonable cost, by using suspension methods. Such methods take advantage of the rapid growth rate of oysters in warmer water, avoid the problem of bottom predators, assure ready accessibility to the oysters, and economize on the amount of space required for culture. In areas where the poor quality of oysters has limited their market acceptance, this approach would seem to have great potential, but obviously it would be successful only where there is opportunity for private leasing.

3. VERTICAL INTEGRATION

The most impressive advances in oyster culture have occurred, and will probably continue to occur, in areas such as Long Island Sound and on the Pacific Coast where vertical integration of the industry is maximized. The same company in effect produces or purchases its own oyster seed, plants them on its own bed, maintains the beds, harvests the oysters, and in most cases processes the oysters for market. Under this system, the producer has exercised complete control throughout, and it is imperative that he insure the quality of his product in order to make a profit on his investment.

In its more primitive form, as in the Southern and Gulf States, the industry is lacking in such integration. The typical oysterman is concerned only with the process of harvesting and accepts whatever price he may receive from the local buyer. His only investment in the operation may be his time, a skiff and a pair of tongs. He relies upon nature or State-financed oyster seeding projects to supply the oysters and has little concern for the oysters once they have been unloaded from his skiff. Particularly since he is dealing with a highly perishable commodity, he can exercise virtually no control over the price structure.

In some cases, the oysters are sold directly to shucking houses. In others, the original buyer may act as distributor to separate processers, perhaps located out of State. In any event, at each exchange, the cost of production must increase. In order for the ultimate price to the consumer to be competitive with other products, it is usually at the original source, i.e., the fisherman, where the price is first reduced.

Where the process of production is so divided into several operating units, each with little interest in the economic efficiency of the others, the chances of organized research leading to improved production is reduced. In fact, it is questionable whether research supported by public funds can really offer any truly constructive and long-range solution to the problems of the industry.

4. PRIVATE RESEARCH

In areas where private corporations are willing to invest in research in oyster culture, the promise of improvement in methods would seem to be greatest. In Long Island Sound, much of the initial research and development work regarding oyster culture, particularly with respect to hatcheries, was done by State and Federal groups; since then, many of the important procedures have been developed by private industry. This would seem to be an appropriate division of responsibility, with basic research undertaken by groups not concerned with profit, while application of research to satisfy immediate needs should be the responsibility of the private producer.

For reasons given earlier, this type of approach, where the producer has a clear incentive to improve production through research, is impractical in a public fishery. Traditionally, fishermen are an independent group of individuals who seldom pool their resources in an effort to improve the fishery. This situation is aggravated all the more if the benefits of their research must be shared by others who did not participate. The necessary capital for meaningful research is seldom available to many oyster fishermen anyhow, who are often scarcely able to earn a living by fishing alone, much less able to divert their profits into research, and many seek other forms of employment during the "off-season".

On the other hand, if the industry is to progress, responsibility for research should not be assumed by State, Federal, or academic groups alone. Funds required for such research may not be readily available. Furthermore, funding agencies may be limited as to the nature of the research they can support, which may not be immediate to the needs of industry. Finally, there is considerable difference in both the time schedule and emphasis of research performed by non-profit, as opposed to profit-motivated, groups.

5. WATER QUALITY

In general, most of the foregoing criteria for a progressive oyster industry are, indirectly or otherwise, linked to the concept of a private, as opposed to public, fishery. In fact, it would seem fair to state that the most primitive terrestrial farmer of today has considerably more control over his economic well-being than the average oystermen working the public beds, since it is within his power, by virtue of private ownership, to improve his land and better his crop production for his own and exclusive benefit.

However, one problem that effects all members of the industry, whether public or private, is the threat of deterioration of the natural environment. San Francisco Bay is an excellent example of a site of a healthy oyster industry that was eliminated as a result of environmental deterioration. As mentioned earlier, a significant portion of Long Island Sound is now closed to oyster operations as a result of pollution, and similar conditions exist along the entire coastline of the continent. It has been suggested by some that oyster production of the future may depend upon systems described in the report by American Cyanamid (1969), whereby the natural environment is replaced by artificial pools, tanks, and, possibly, artificial seawater.

The development of hatchery techniques as a means of avoiding the uncertainties of natural production has shown great promise; it is disturbing to note that the continuance of at least two shellfish hatcheries is threatened by the occurrence of insecticides in their water systems. Clearly, the same could occur to culture operations based upon the use of artificial ponds and pools, if the water used for culture was drawn from the natural environment.

For the most part, oyster producers operate on a very marginal basis. If an additional cost of depuration is added to their overall costs, it is possible that oysters will price themselves out of the market. Unfortunately, the value of a local oyster industry, and the ability of those engaged in the industry to organize in their own defense, is seldom sufficient to prevent environmental modifications detrimental to the industry

The two great needs facing the industry today are, therefore, an increase in public awareness of the serious implications of continued environmental alterations, and a review, at the State level, of the laws governing the use of natural waters for private culture purposes.

A shucking house

APPENDIX I

Information contained in this report is based in part upon interviews with the following individuals, whose time and cooperation are gratefully acknowledged:

Dr. J. D. Andrews, Virginia Institute of Marine Science, Gloucester Point, Virginia

Mr. Chester Belknap, Belon Oysters of California, Inc., Morro Bay, California

Mr. Luther Blount, Bristol, Rhode Island

Dr. W. P. Breese, Department of Fisheries and Wildlife, Oregon State University, Newport, Oregon

Mr. William W. Budge, Pacific Mariculture, Inc., Pescadero, California

Dr. A. F. Chestnut, Institute of Marine Sciences, University of North Carolina, Morehead City, North Carolina

Mr. Joseph V. Colson, Executive Director, Gulf States Marine Fisheries Commission, New Orleans, Louisiana

Mr. Walter Dalstrom, California Department of Fish and Game, Menlo Park, California

Mr. Harry G. Davis, Biological Laboratory, U.S. Bureaus of Commercial Fisheries, Milford, Connecticut

Mr. Roy Drinnan, Fisheries Research Board of Canada, Ellerslie, Prince Edward Island, Canada

Mr. J. Dunathan, Oceanography Mariculture Industries, Riviera Beach, Florida

Dr. John Dupuy, Virginia Institute of Marine Science, Gloucester Point, Virginia

Mr. James Engle, Biological Laboratory, U.S. Bureau of Commercial Fisheries, Oxford, Maryland

Mr. Edward Fordham, Shellfish Laboratories, Stratford, Connecticut

Dr. Robert Hanks, Biological Laboratory, U.S. Bureau of Commercial Fisheries, Oxford, Maryland

Dr. Harold Haskins, Department of Zoology, Rutgers University, New Brunswick, New Jersey

Dr. Dexter Haven, Virginia Institute of Marine Science, Gloucester Point, Virginia

Mr. George Henderson, Malpeque Oyster Cultures, Inc., Conway, Prince Edward Island, Canada

Dr. Herbert Hidu, Chesapeake Research Institute, Solomons, Maryland

Mr. Robert Hofstetter, Texas Parks and Wildlife Department, Seabrook, Texas

Dr. Robert Ingle, Florida Department of Conservation, Tallahassee, Florida

Mr. Charles Johnson, Johnson Oyster Company, Inverness, California

Mr. E. Joyce, Florida Board of Conservation, Marine Laboratory, St. Petersburg, Florida

Mr. Warren S. Landers, Biological Laboratory, U.S. Bureau of Commercial Fisheries, Milford, Connecticut

Mr. Howard Marshall, Department of Conservation and Development, Morehead City, North Carolina

Dr. Donald Mauer, Biological Laboratory, University of Delaware, Lewes, Delaware

Mr. William Moore, Texas Parks and Wildlife Department, Pelacios, Texas

Mr. J. Richards Nelson, Long Island Oyster Farms, New Haven, Connecticut

Mr. F. Ward Paine, Ocean Science Capital Corporation, Palo Alto, California

Dr. D. B. Qualye, Fisheries Research Board of Canada, Nanaimo, British Columbia

Mr. Joseph Quick, Florida Department of Conservation, St. Petersburg, Florida

Mr. Timothy Schink, Washington Department of Fisheries, Brinnon, Washington

Mr. William N. Shaw, Biological Laboratory, U.S. Bureau of Commercial Fisheries, Oxford, Maryland

Mr. R. N. Steele, Rock Point Oyster Company, Blanchard, Washington

Mr. Max Summers, Louisiana Wildlife and Fisheries Commission, New Orleans, Louisiana

Mrs. David H. Wallace, Oyster Institute of North America, West Sayville, Long Island, New York

Mr. William Q. Wick, Marine Science Center, Marine Science Drive, Newport, Oregon

Mr. J. Yamashita, Western Oyster Company, Purdy, Washington

APPENDIX 2

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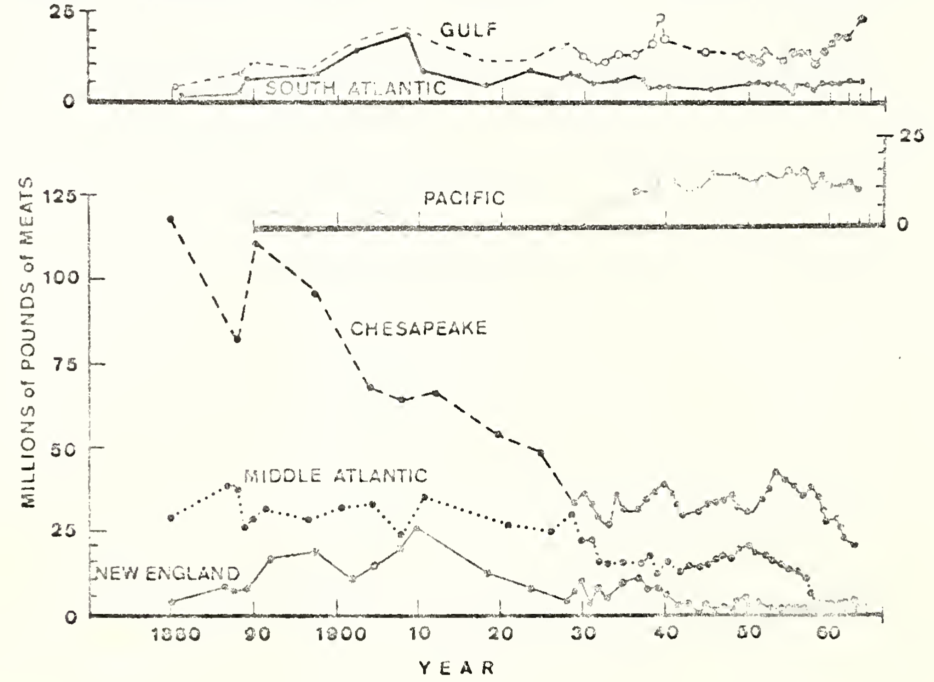
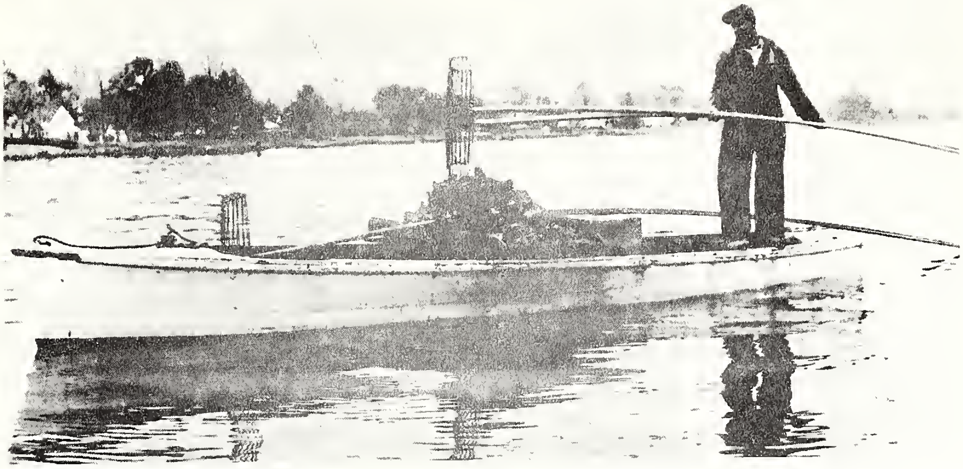
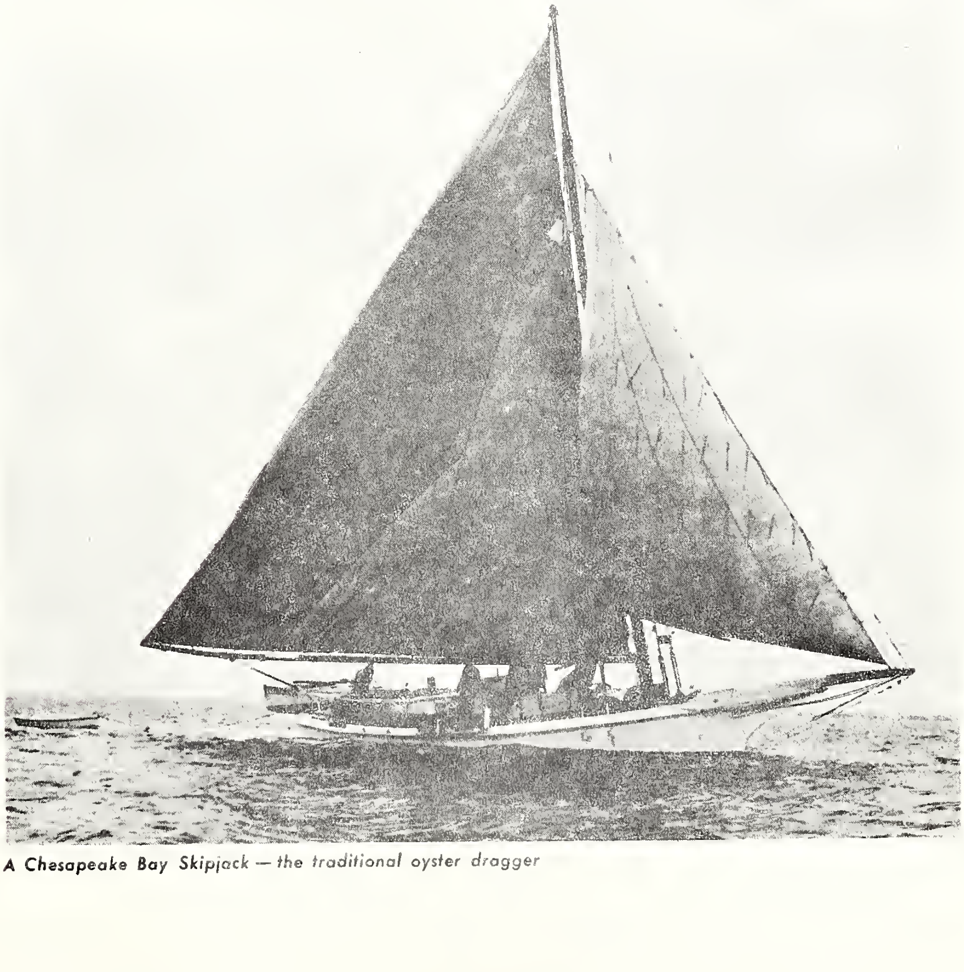


U.S. OYSTER PRODUCTION ...... BY REGION



Hand-tonging in Chesapeake Bay



A Chesapeake Bay Skipjack — the traditional oyster dragger

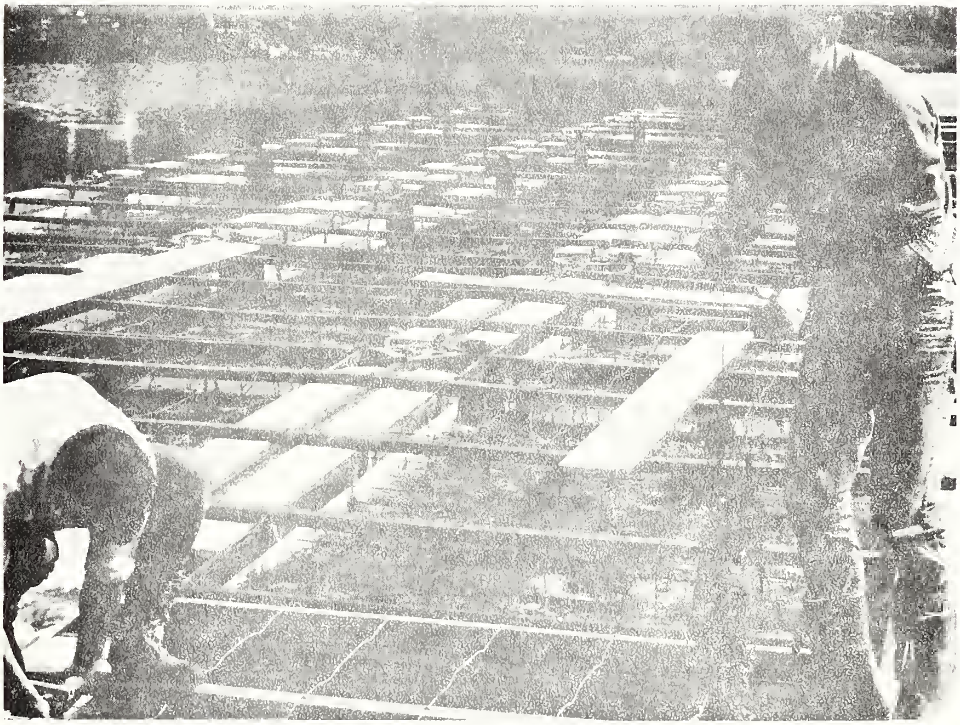
Oyster culture rafts at the BCF Biological Laboratory, Oxford, Md.

Fixed racks for string-culture of oysters

Bureau of Commercial Fisheries (U.S. Dept. of Interior, Fish and Wildlife Service) **Biological Laboratory, Oxford, Md.** showing experimental oyster ponds

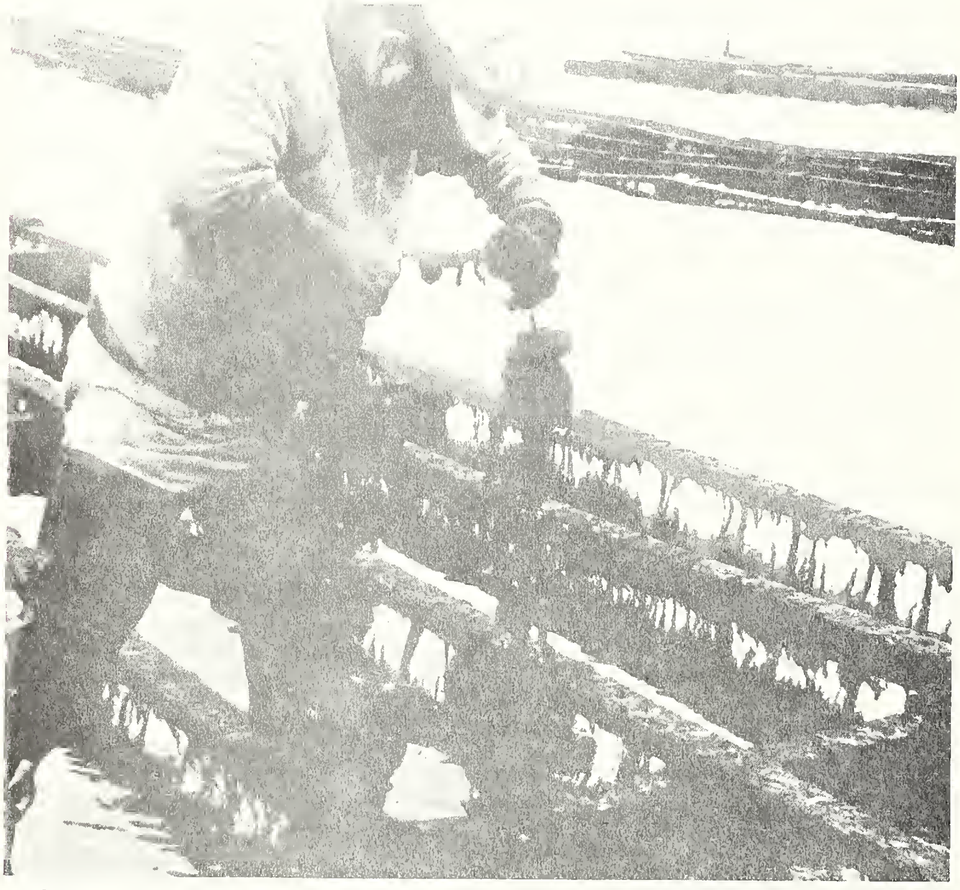
Solarium, used for the culture of algae, abutting oyster hatchery on Prince Edward Island

Oyster culture rafts linked together in Bristol, Rhode Island



Raft culture of oysters in Bristol, Rhode Island

Piles of oyster shell to be used as culch, New Haven, Conn.



Pacific oysters grown by hanging culture method from fixed rocks, Drake Estero, Calif.

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